

*JUNIPERUS VIRGINIANA* ENCROACHMENT INTO  
MESIC GRASSLANDS: RAINFALL INTERCEPTION  
AND TREE WATER USE

By

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“Some people come into our lives and quickly go. Some people move our souls to dance. They awaken us to a new understanding with the passing whisper of their wisdom. Some people make the sky more beautiful to gaze upon. They stay in our lives for awhile, leave footprints on our hearts, and we are never, ever the same.” (Flavia Weedn)

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USE

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**ABSTRACT:** *Juniperus virginiana* is encroaching into the Great Plains of the United States at an alarming rate causing ecological and economic harm. *Juniperus virginiana* expansion alters the species diversity, soil properties, and water balance. Determining how *J. virginiana* changes tallgrass prairies water balance is extremely important to maintain the ecosystem services of these ecosystems. The objectives of this study were to quantify and evaluate which factors affect *J. virginiana* canopy interception and water use. Twenty five trees of different diameters from both closed and open grown stands were used. To quantify canopy interception, throughfall and stemflow were measured for each tree during 47 rainfall events. We measured tree water use during the 2011 calendar year using the thermal dissipation technique described by Granier. Environmental factors were measured at the site to determine their effects on canopy interception and water use. Both experiments were performed in encroached tallgrass prairie watersheds near Stillwater, OK.

*Juniperus virginiana* canopies intercepted an average of 37% of the total rainfall during the study period. Small rainfall events were almost totally held by *J. virginiana* canopies. Around 20% of the precipitation from the largest events of high intensity were intercepted by the canopy. Stemflow averaged 7% of rainfall for all trees. Throughfall was mainly explained by three storm characteristics: rainfall amount, intensity and duration. Tree characteristics, rainfall amount and duration were the main factors influencing stemflow. All *J. virginiana* trees used water year-round. Average daily water use ranged from 2 liters to 80 liters, for trees of 2 and 31 cm DBH, respectively. The maximum daily water use was 152 liters for a 31 cm DBH open grown tree. Water use fluctuation was mainly explained by daily potential evapotranspiration, vapor pressure deficit, maximum temperature, solar radiation, and volumetric soil water content between 0-10cm. Results from both experiments will later be used to scale *J. virginiana* canopy interception and water uptake to whole watersheds.

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## CHAPTER I

### GENERAL INTRODUCTION

#### 1. Introduction

The conversion of grasslands into woodlands due to woody plant encroachment has been an ecosystem problem reported worldwide. *Juniperus virginiana* (eastern redcedar) is the primary woody species encroaching the Great Plains in the United States (Fuhlendorf, 1999; Briggs et al., 2002a; Engle et al., 2007). Currently, 30% of the grasslands and rangelands can be classified as *J. virginiana* woodland (Engle et al., 2007). However, according encroachment is predicted to grow exponentially at the expense of native grassland (Engle et al., 1996). In the state of Oklahoma, around 12.6 million acres of rangelands and grasslands are projected to be encroached by *J. virginiana* by 2013 totaling a loss of \$447 million (NRCS, 2010). *Juniperus* sp. is invading Texas, Kansas and Nebraska states similar intensity (Knapp et al., 2008).

Woody species encroachment alters the grassland micro-environment. *Juniperus virginiana* expansion into grasslands decreases herbaceous species diversity (Gehring and Bragg, 1992; Linneman and Palmer, 2006); changes soil hydrological properties and nutrient cycles (Broadfoot, 1951; Norris et al., 2001a; Bekele et al., 2006); and alters the ecosystem water balance (Engle et al., 1987; Axmann and Knapp, 1993).

Water balance accounts for the water input to, distribution within, and output from an ecosystem. The input is by precipitation, the water is distributed by infiltrating the soil or flowing through the soil surface, and the output occurs mainly as streamflow and by evapotranspiration. Evapotranspiration includes transpiration from plants and evaporation from bare soil or intercepted water by litter and vegetation surfaces. Rainfall interception by vegetation largely affects the fraction of precipitation reaching the soil surface. The loss of water by transpiration impacts the soil water content. Quantifying these two components and their variabilities is very important to understand the water budget of a specific ecosystem.

Arid and semiarid ecosystems commonly have a large number of rainfall events between 2 and 5 mm (Loik et al., 2004). Small events result in higher amounts of rainfall interception when compared to larger events. Large storms likely produce more streamflow. Therefore, precipitation interception is critical semi-arid regions because it dramatically alters the amount, spatial distribution, and timing of precipitation input to the soil. Compared to grasses, trees usually have greater leaf areas (Carlyle-Moses, 2004) and root that extend beyond the canopy (Scholes and Archer, 1997), that potentially increase rainfall interception and water uptake. If *J. virginiana* encroachment results in increased evapotranspiration, this may reduce streamflow. In fact, several studies have reported that woody plant invasion decreases streamflow (Owens et al., 2006; Tennesen, 2008; Wilcox, 2008).

My thesis contains two separate studies; the first one evaluated *J. virginiana* rainfall interception and the second focused on *J. virginiana* water use. Both were conducted in a mesic prairie of the eastern Great Plains. Individual trees from a

representative size distribution were used and results were scaled to the watershed scale. These two studies are important contributions to better understand the changes caused by *J. virginiana* encroachment to the tallgrass prairie water balance.

## **2. Overview**

### **2.1. *Juniperus virginiana***

*Juniperus virginiana* L. (eastern redcedar) is a widely distributed coniferous tree in the Cupressaceae family that is native to every state east of the 100<sup>th</sup> meridian in the United States (Lawson, 1986). This species grows slowly and can reach 30 m high and 120 cm DBH (diameter at breast height) on good sites, but may only reach shrub size on poor sites (Lawson, 1986). The species is mostly dioecious. Males have stiffer branches, are russet-brown in winter time and the pollen-bearing cones give the whole tree a yellow color. Females are green year round and the fruit is a fleshy dark-blue berry-like cone (Kent, 1900; Lawson, 1986). After trees reach ten years or older, seeds and masts production occur yearly, and mast crops are often produced every two years.

The *J. virginiana* trunk is irregularly shaped, the bark is thin and peels in long strips. Tree crown shape varies. They can have a triangular/pyramidal and or columnar form with the branches ascending, wide-spreading or leaning. The leaves are about 3 mm long and have a needle-like shape in juvenile stage, and mature leaves have an acute tip and overlap (Kent, 1900; Lawson, 1986). During the first year, root development is greater than aboveground growth. The root system is long and fibrous during the seedling stage, and develops a taproot when mature (Lawson and Law, 1983). Potentially, juniper trees have a deep effective rooting system, that is able to access water at depths that

grasses roots are not able to reach (Huxman et al., 2005; Tennesen, 2008). According to Jackson et al. (1996), in a temperate environment grasses have 40% of rooting system concentrated in the top 10 cm, while conifers have 50% of their roots below 30cm.

However, in sites with a shallow water table or with rocky soils *J. virginiana* can maintain the fibrous form and concentrate root development in the available soil (Williamson, 1965). *Juniperus virginiana* is drought tolerant. It has low stomatal conductance, can open stomata at low soil water potentials and has high water use efficiency (Eggemeyer et al., 2006; Willson and Jackson, 2006). As a result, it can maintain its physiological activity during periods of very low water available (Bahari et al., 1985). In general, the genus *Juniperus* is known to be resistant to xylem cavitation (Willson and Jackson, 2006). In addition, these species store water in apoplastic spaces when the tree is under water stress which further delays the effects of low soil water availability. However, according to Willson et al. (2008), *J. virginiana* is the less resistant than several other juniper species, and reaches 50% loss of conductivity at - 5.8 MPa in stems and - 4.9 MPa in roots. This is lower than those compared to other co-occurring species such as those from the genus *Quercus* that show stomatal closure and the effects of water stress at leaf water potentials between -1.85 MPa and -3.70 MPa (Abrams, 1990).

*Juniperus virginiana* is widely distributed through its natural range. It occurs in limestone derived soils, but it can grow in different topographic areas, from deep to shallow soils, from ridge tops to bottom lands (Harper, 1912). It can also grow under diverse and extreme climatic conditions (Lawson and Law, 1983). Within its range, the average annual precipitation varies from 380 mm to 1525 mm, average annual snowfall

averages from 0 to 2540 mm, average temperature ranges from 3.9°C to 20°C, the maximum average temperature is 40°C and the minimum average is -40°C (Lawson and Law, 1983). Besides its adaptability, this species has been expanding its range and has spread to grasslands, rangelands, abandoned fields, and forests (Owensby, 1973; Ormsbee et al., 1976; Lawson, 1986; Bidwell et al., 2002; van Els et al., 2010).

Fire is probably the primary factor preventing *J. virginiana* expansion. Due to this species' thin bark and fibrous root near the soil surface, it can be easily injured by fire (Lawson and Law, 1983). In addition, *J. virginiana* cannot resprout when top killed (Owensby, 1973). However, the susceptibility to surface fire decreases once trees reach 1.5 m of height (Engle et al., 1988).

## **2.2. Woody plant Encroachment**

Over the past century, grasslands have been encroached by woody plants worldwide (Bragg and Hulbert, 1976; Archer, 1995; Archer et al., 2001; Bond et al., 2005; Huxman et al., 2005). This shift from rangelands to woodland is coincident with increases in human populations and consequent to changes in land use and natural disturbances (Archer et al., 2001). Due to fire suppression and over grazing, higher amounts of litter have accumulated, grass biomass production has declined, and woody vegetation has become established (Briggs et al., 2002a; Bond et al., 2005; Eggemeyer et al., 2006). It has also been proposed that woody plant encroachment is linked to changes in world temperature and precipitation regime (Hastings and Turner, 1967; Van Auken, 2000) as well as to rising levels of atmospheric CO<sub>2</sub> (Mayeux et al., 1991; Idso, 1992; Johnson et al., 1993; Archer et al., 2001). Some genera that are encroaching grasslands

include: *Acacia*, *Yucca*, *Flourensia*, *Haplopappus*, *Opuntia*, *Quercus*, *Gutierrezia*, and *Juniperus* (Van Auken, 2000).

#### *Juniperus virginiana* encroachment

*Juniperus virginiana* is the main *Juniperus* species that is encroaching into mesic prairies in the eastern Great Plains (Schmidt and Stubbendieck, 1993; Fuhlendorf, 1999; Briggs et al., 2002a; Briggs et al., 2002b; Engle et al., 2007). In Oklahoma, around 12.6 million acres of rangelands and grasslands are projected to be encroached by *J. virginiana* by 2013, totaling a loss of \$447 million dollars through loss of environmental services (NRCS, 2008). Further, this specie is invading Texas, Kansas and Nebraska at similar intensities (Knapp et al., 2008). In 2007, the *J. virginiana* canopy cover in the southern part of the Great Plains was close to 30% (Engle et al., 2007). However, according to Engle et al. (1996), *J. virginiana* encroachment is predicted to grow exponentially, and can lead to loss of grasslands altogether in certain locations.

Historically, juniper species mainly grow on shallow soils and rocky ridges that are protected from fire (Harper, 1912; Burkhardt and Tisdale, 1976). However, junipers have recently been rapidly expanding in grasslands and woodlands. Even though this type of encroachment has been explained by climate change (Hastings and Turner, 1967), evidence shows that juniper trees are moving down in elevation, and not up in elevation as a warmer climate would implicate (Van Auken, 2000). Thus, fire suppression and a reduction in grass biomass have been indicated as the main causes of *Juniperus* sp. expansion into prairie areas (Owensby, 1973).



*Juniperus virginiana* encroachment suppresses the native herbaceous species in prairie ecosystems, converting grasslands to closed juniper stands with dense canopies. Several studies found that *J. virginiana* decreased the richness and quantity of prairie species (Jameson, 1970; Engle et al., 1987; Gehring and Bragg, 1992; Bidwell et al., 2002; Limb et al., 2010). The reduction in species diversity caused by *J. virginiana* is directly related to the density of the stand. There is a higher diversity of prairie species as the distance from *J. virginiana* trunks increases (Linneman and Palmer, 2006). The relationship between *J. virginiana* density and herbaceous vegetation occurs due to the reduction of light and precipitation reaching the soil. Dense *J. virginiana* canopies can reduce 80% of the light reaching the forest floor (Jameson, 1970). In addition, redcedar's leaf litter covers the soil surface and probably prevents seed germination and plant development (van Els et al., 2010). Moreover, redcedar's root system competes for water as well as soil space with grass roots (Jameson, 1970).

*Juniperus virginiana* can also alter the prairie vegetation community by altering soil properties. Due to lower light availability, increasing woody plant cover decreases soil temperature (Breshears et al., 1998; Chambers, 2001). Redcedar tends to buffer soil acidity, due to the high amount of cations in its leaves (Coile, 1933; Read and Walker, 1950). Furthermore, the high litter accumulation and microclimate created by *J. virginiana* stands may slow decomposition compared to grasslands (Norris et al., 2001a; Norris et al., 2001b). In this way, *J. virginiana* encroachment may increase organic matter input to the soil and increase nitrogen immobilization. Higher N immobilization would contribute to a reduction in the potential production of grasses, but not in *J.*

*virginiana* which has a greater ability to sustain a higher productivity under low N conditions than most prairie species (Norris et al., 2001a).

#### *Juniperus virginiana* encroachment and the water balance

Annual actual evapotranspiration tends to be higher in woodlands than in grasslands due to greater canopy interception and transpiration. Trees generally have a greater leaf area index and more extensive root systems than grasses (Carlyle-Moses, 2004; Scholes and Archer, 1997). Thus, some studies have suggested mechanisms that woody plant encroachment into grasslands could lead to a reduction in streamflow (Huxman et al., 2005; Owens et al., 2006; Wilcox and Thurow, 2006; Schwinning, 2008; Tennesen, 2008; Wilcox, 2008). Woody plants root systems probably create soil macropores and leave a permeable soil structure that increases infiltration capacity and hydraulic conductivity. Macropores allow water to move rapidly and deeply into the soil. In this way, *J. virginiana* encroachment into grasslands likely results in changes in water yield.

*Juniperus* sp. morphology is conducive to intercepting large amounts of precipitation due to a high leaf area index (Owens et al., 2006). Annual interception losses in *Juniperus* sp. can reach a maximum of 46% of rainfall in rangelands (Young et al., 1984; Wilcox and Thurow, 2006; Wilcox, 2008). Owens et al. (2006) found that rainfall events  $\leq 2.5$  mm were completely held by the canopy and 50% of an 11 mm size storm was intercepted by Ashe juniper (*J. ashei*) canopies. In the same study, 5% of the rainfall was delivered to the base of the Ashe juniper trees as stemflow for events  $> 2.5$  mm. Western juniper (*J. occidentalis*) was found to exhaust soil water content, reducing

water availability to herbaceous vegetation (Angell and Miller, 1994). Broadfoot (1951) found that soil under *J. virginiana* has 10% less moisture than under grasses in north central Mississippi. However, soil moisture under *J. virginiana* may vary across seasons (Freeman, 1933).

Compared to grasses, *Juniperus* sp. differs by being evergreen and having the ability to access deep soil water (Huxman et al., 2005). *Juniperus virginiana* can keep their stomata open even in extremely dry conditions. Lassoie et al. (1983) found that *J. virginiana* trees just closed their stomata during a severe hot and dry period, only reducing transpiration by 30% compared to periods with high evaporative demand with lower leaf temperatures and higher soil water availability. In addition, photosynthesis in *J. virginiana* decreases during winter, but it remains positive (Eggemeyer et al., 2006). *Juniperus virginiana* transpiration is greater during spring, when environmental and physiological factors are more favorable (Lassoie et al., 1983; Bahari et al., 1985; Eggemeyer et al., 2008). Eggemeyer (2006) found that grasses senesce during dry periods and are unable to recover. In contrast, *J. virginiana* has the ability to recover when environmental conditions improve. Transpiration may be influenced by stand density and tree growth type. Owens (2008) showed that Ashe juniper trees in open canopies transpire more than those beneath older trees in a closed canopy because of light limitation.

Dry and mesic environments are characterized by a higher annual potential evapotranspiration than annual precipitation (Garbrecht et al., 2004). *Juniperus virginiana* encroachment into mesic grasslands will potentially raise evapotranspiration

by increasing water uptake and rainfall interception. Thereby, this encroachment probably will reduce water distributed as streamflow.

### **2.3. Water balance**

The water balance equation for a small upland watershed is (USGS, 2008):

$$P = ET + Q + G + \Delta S$$

where: P= gross precipitation, ET= evapotranspiration, Q= streamflow, G=groundwater recharge,  $\Delta S$ =change in soil water storage. Based on the water balance concept, an increase in evapotranspiration (ET) should result in a decrease in streamflow, groundwater recharge or soil water storage. Evapotranspiration is composed of transpiration, as well as evaporation of water intercepted from the canopy and from the soil and open water. In grassland, forested and other heavily vegetated watersheds, transpiration and interception are the largest components of ET. Therefore, if changes in vegetation change ET, streamflow and groundwater recharge will probably change.

#### **2.3.1. Rainfall interception**

Before precipitation reaches the soil vegetation can intercept it. Interception is the first process to determine the amount of water that is going to reach the soil (Loik et al., 2004). The amount of precipitation that reaches the soil is determined by species type and condition of the vegetation. According to Brooks et al. (2003), canopy interception ( $I_c$ ) can be determined by the following equation:

$$I_c = P - T - S$$

where:  $P$  = gross precipitation, which is the rainfall amount before it reaches the vegetation and soil;  $T$  = throughfall, is the rain that reaches the soil by dripping off the canopy or passing through canopy openings;  $S$  = stemflow, which is the water that flows along plant stems to the soil.  $P_n$  (net precipitation) is the total precipitation that reaches the soil and is the sum of  $T$  and  $S$ .

The terminology and equations used in canopy interception studies vary and have not been standardized (Xiao et al., 2000). Therefore, interception can be influenced and calculated considering some different and complementary processes. The interception process depends on the canopy storage capacity, which is the amount of water that can be held by the vegetation canopy and either be evaporated, absorbed by vegetation surface or fall to the ground as canopy drip when the storage capacity is exceeded (Horton, 1919). Throughfall and canopy drip are difficult to separate, but the concept of each can be used to explain the variability in the amount of water reaching the soil under a canopy (Crockford and Richardson, 1990).

Another variable that can influence  $P_n$  is litter interception, which is the amount of water that can be held by litter and evaporated. Water lost to litter interception is prevented from reaching the soil. Depending on the method of measurement and on the species in consideration, litter interception can significantly increase interception losses (Silva and Rodriguez, 2001; Carlyle-Moses, 2004; Linneman and Palmer, 2006; Owens et al., 2006).

Stemflow

Stemflow is water that flows along the outside of the tree trunk. Its magnitude is determined by precipitation amount, intensity, and duration, and by species characteristics (Martinez-Meza and Whiford, 1996). Stemflow averages about 8.2% of rainfall, depending on the species type and cover density (Carlyle-Moses, 2004). In tropical forests, where rainfall occurs with high intensity, single trees are able to generate high amounts of stemflow (up to  $26\% \pm 18\%$  s.e.) but the overall stemflow percent decreases ( $1.8\% \pm 1\%$  s.e.) when considering whole stands that characterizes the dense canopy structure of tropical forests (Lloyd and Marques, 1987). In arid environments stemflow can have different magnitudes. Stemflow has been shown to account for 0.6%, 0.5% and 0.03% in a pine, oak and pine-oak forests, respectively, in northeastern Mexico (Silva and Rodriguez, 2001). Stemflow on a multi-stemmed shrub from a semiarid area in Mexico was 45% during an intense storm simulation (Mauchamp and Janeau, 1993). Stemflow occurs more effectively during rainfall events after rainy days, when the bark is already saturated (Rutter et al., 1975). Stemflow likely does not occur in storms of less than 5 mm (Silva and Rodriguez, 2001).

Vegetation characteristics such as the distribution of branches, bark roughness, and canopy cover also affect stemflow (Martinez-Meza and Whiford, 1996; Xiao et al., 2000; Crockford and Richardson, 2006). Crockford and Richardson (2006) determined that tree and crown size, leaf and branch shape and angle, and trunk shape and roughness were all central factors that influence stemflow. During a heavy rainfall event, *Fagus* sp. generated stemflow of 10% of P compared to 2% generated from *Pinus* sp. (Horton, 1919). Trees with smooth barks permit water to flow quickly down the stem, and result in higher stemflow volumes. On the other hand, rougher barks are able to absorb more water

increasing the water intercepted. In fact, stemflow has been found to be minimal in rough-bark species (Lankreijer et al., 1993; Link et al., 2004). Further, the presence of leaves also influence stemflow volume, Xiao et al. (2000) reported that stemflow was 8% for a broadleaf deciduous pear tree (*Pyrus calleryana*) while for a broadleaf evergreen oak tree (*Quercus suber*) with the similar shape but slightly smaller crown, was 15%.

Overall, stemflow contributes to the amount of the water reaching the soil; it also redistributes water and nutrients into islands of fertility. The water that is funneled to the tree's base as stemflow may replenish soil moisture by rapidly infiltrating the soil surface (Devitt and Smith, 2002) or by slowly being redistributed (Schwinning and Sala, 2004). In addition, both throughfall and stemflow wash nutrients from the plant surface to the soil (Klemmedson et al., 1983; Silva and Rodriguez, 2001). Thereby, this moist and nutrient-rich area beneath the tree will be more suitable for individual vegetation development (Wolters et al., 2000). Stemflow can concentrate water near the stem up to 21 times greater than gross precipitation if the area of impact is assumed to be  $0.5 \text{ m}^2$  (Owens et al., 2006). Thus, stemflow water benefits the competition between species by funneling water to individual plant stem (Ndawula-Senyimba et al., 1971). Others have used the concentration of water to the stem base as an explanation of how certain species survive droughts (Carlyle-Moses, 2004).

#### Interception variability

Canopy interception accounts for a large amount of water loss from a vegetated watershed (Carlyle-Moses, 2004). Horton (1919) affirmed that interception losses by forests stands can account for 15 to 80% of a precipitation event, depending on the

species type and age and stand density. Conifers can intercept 20 to 40% of gross precipitation and hardwoods 10 to 20% (Zinke, 1967). Roth et al. (2007) asserted that tree canopy interception can range from 10 to 50% of gross precipitation. Carlyle-Moses and Gash (2011) conducted a literature review of canopy interception studies, and found that interception in mixed forests ranges from 14 to 25% of precipitation, in hardwood forests 20 to 40%, and in coniferous forest that intercepted 19 to 45% of precipitation.

The amount of rainfall intercepted is controlled by species-surface canopy storage capacity, precipitation type, amount, duration and intensity, weather characteristics and the evaporation rate during precipitation (Horton, 1919; Rutter et al., 1971; Crockford and Richardson, 1990; Breshears et al., 1998; Owens et al., 2006; Carlyle-Moses and Gash, 2011). Based on data from three different trees species, Carlyle-Moses and Gash (2011) found that as precipitation amount increases, the percent of P intercepted decreases exponentially and approaches a constant amount. Therefore, small rainfall events will be intercepted in greater percentages than high intensity events (Figure 1). The precipitation quantity, timing and intensity influence the interception process and determine water balance component magnitudes (Loik et al., 2004; Schwinning and Sala, 2004; Owens et al., 2006). In semiarid areas during storms events with periods of both high and low intensities, the interception rate is different during each period as if two separate events (Owens et al., 2006). Interception may be greater during periods of series of small rainfall events then during series of few large events (Carlyle-Moses and Gash, 2011). Event frequency and continuity also influence rainfall interception. A gap between events could facilitate the evaporation of water held by the vegetation, thereby enhancing the canopy storage capacity of the next event (Zeng et al., 2000).



The percent of precipitation intercepted is directly affected by the evaporation of rainfall held in the canopy and tree surface from previous events (Carlyle-Moses and Gash, 2011). Canopy structure and closure influence interception likewise. Trees growing apart from each other results in an open grown structure characterized by maximum canopy size and branches (Teklehaimanot et al., 1991). In stands with full canopy closure, crowns of adjacent trees may overlap each other decreasing the evaporation capacity (Horton, 1919). Less light reaches the interior of the stands and lower branches die off, this results in shallower canopies compared to trees with open grown characteristics (Xiao et al., 2000). Overlapping canopies in dense stands will prevent air circulation and keep moist air around leaves reducing evaporation of intercepted water (Teklehaimanot et al., 1991). While open grown trees can have higher interception due to improved airflow, wind can also decrease the amount of water held by the canopy. Wind shakes tree leaves and branches (Hörmann et al., 1996) and also changes leaf and branch angles (Xiao et al., 2000), making water fall as throughfall. Stogsdill et al. (1989) compared interception in loblolly pine stands of different densities in Oklahoma and found that each  $4\text{m}^2$  per hectare of basal area added to the stand reduced throughfall amount by 3%.

### **2.3.1. Water use**

Evapotranspiration (ET) represents the water that evaporates from vegetation and soil surfaces together with the water that escapes plants from stomata openings and return back to the atmosphere as transpiration (Wilcox et al., 2003). Transpiration is the dominant process regarding plant water relations, because plants transpire a large volume

of water daily (Kramer and Boyer, 1995). Controlled by vapor pressure deficit (VPD) and by stomatal guard cells, this process also regulates the energy gradient within the soil-plant-atmosphere continuum which will largely controls water absorption and ascent of sap (Kramer and Boyer, 1995; Sperry et al., 2003). At plot scale, ET can be directly measured using an energy balance budget approach such as the Bowen ratio method (Bowen, 1926) or eddy covariance technique (Berbigier et al., 1996; Tang et al., 2006; Mackay et al., 2007; Moore et al., 2008). Energy balance is broadly used to account for evapotranspiration, but it can not effectively separate transpiration from evaporation. Thus, several measurements based on a water budget approach have been used to better quantify the total transpiration of trees canopy.

Some techniques to estimate whole-tree water uptake were reviewed by Wullschleger et al. (1998). Among those cited were the use of lysimeters, large tree photometers, tent enclosures or ventilated chambers, energy-balance, heat dissipation and heat-pulse techniques. According Wullschleger et al. (1998), the heat dissipation and heat balance are the most accessible, due to their relative simplicity, possibility to use remote operation, and lower costs. These techniques assume that sap flow is equivalent to transpiration (Smith and Allen, 1996) and measure ascent of sap by using temperature measurements as a tracer as first described by Huber and Schmidt, (1937). Sap flow is a biological term that refers to the water moving through the conductive xylem. This term can be expressed in unit volume per unit stem circumference, and once it is scaled to a sapwood area basis it is called as sap flux.

A variety of techniques have been developed to measure sap flow, such as the following: heat pulse velocity (Marshall, 1958), the tissue heat balance (Čermák et al.,

1973), thermal dissipation (Granier, 1985), and heat field deformation (Nadezhdina et al., 1998). Between the cited techniques, all have advantages and disadvantages (Smith and Allen, 1996; Kostner et al., 1998; Wullschleger et al., 1998). However, the thermal dissipation technique is currently the most widely used for forest sap flow measurements. It has been used with different types of forests: boreal (Duursma et al., 2008), temperate (Herbst et al., 2007), tropical (Chapotin et al., 2006), savanna (Do et al., 2008), plantation (Samuelson et al., 2008), and orchard (Reis et al., 2006). It has been used in palms (Renninger and Phillips, 2010) and bamboos (Kume et al., 2010). Its common use is because thermal dissipation sensors are relatively easy to install, less expensive, and require lower energy source (Andrade et al., 1998; Steppe et al., 2010), and can be used to get continuous long-term estimations of sap flow (Saugier et al., 1997). In addition, conversion of measured temperature differentials to sap flow does not requires complicated calculations (Smith and Allen, 1996).

#### Thermal dissipation technique (TDP)

First developed by Granier (1985), the thermal dissipation technique estimates canopy transpiration and can be used to determine canopy stomatal conductance in response to environmental factors. This technique relies on the temperature difference between two probes placed radially into the tree trunk ~4 cm apart from each other. The upper probe contains a heater and a thermocouple that is referenced to another thermocouple in the lower probe, which is unheated (Figure 2). The difference in temperature between both probes ( $\Delta T$ ) is dependent on sap movement;  $\Delta T$  is inversely related to water movement as sapflux carries heat upwards away from the thermocouple.

Using three woody species, *Pseudotsuga menziesii*, *Pinus nigra*, and *Quercus pedunculata*, Granier (1985) generated an empirical relationship between sap flow velocity (V) and  $\Delta T$ :

$$V = 0.0119 * K^{1.231}$$

where, 0.0119 and 1.231 are adjusted values, and K is dimensionless:

$$K = (\Delta T_{\max} - \Delta T) / \Delta T$$

where,  $\Delta T_{\max}$  is the temperature difference between the heater and reference probe when there is no sap flow and  $\Delta T$  is the temperature difference any other time. Sap flux is then calculating incorporating sapwood area ( $\text{cm}^2$ ):

$$F_s = SA * V * 3600 \text{ (cm}^3/\text{h)}$$

where, multiplying  $F_s$  by 3600 converts  $F_s$  units to  $\text{cm}^3 \text{ h}^{-1}$ .

Even though the technique described above is the most used in forests, there are some drawbacks of using this technique that can result in over or underestimation of whole-tree water use. Granier TDP, as other heat based techniques, requires the estimation of the  $\Delta T_{\max}$ , obtained from a period of zero sap flow. A period of zero sap flow is assumed to occur during nighttime, and the value of maximum temperature differential between both probes would be recorded predawn. However, the determination of  $\Delta T_{\max}$  is not simple, because there are cases where sap flow does not cease overnight. Some trees may maintain open stomata during night (Snyder et al., 2003; Ford et al., 2004; Kavanagh et al., 2007). Also water may continue to move within the

tree due to redistribution in roots (Burgess et al., 2000) and refilling of roots or stem vessels to maintain water potentials above the point of xylem dysfunction (Lu et al., 1996). Moreover, radial sap flux density varies with time and scaling measurements to the whole sapwood can result in errors (Mark and Crews, 1973; Lassoie et al., 1977; Ford et al., 2004). Xylem suffers diurnal changes and individual vessels can shrink under water stress without breaking the water column (Zimmermann, 1983). In addition, natural temperature gradients can occur along the stem radial profile what causes errors when using the TDP approach (Kostner et al., 1998; Tatarinov et al., 2005).

Another drawback is the adjusted values generated from the empirical equation (equation 1) derived by Granier (1985). While some support the accuracy of Granier's adjusted equation for different species (Loustau et al., 1996; Lu and Chacko, 1998; Braun and Schmid, 1999; McCulloh et al., 2007), others argue that it varies with species (Lu et al., 2004; Bush et al., 2010; Steppe et al., 2010). In fact, Smith and Allen (1996) have advised that parameters should be calibrated for each species separately. Moreover, many researchers construct their own sensors. Sometimes the material used together with the electrical power applied may affect the accuracy of this technique (Lu et al., 2004).

#### Water use variability

Water moves through the soil-plant-atmosphere continuum along a gradient of decreasing water potential from soil, through the plant, to the atmosphere. Transpiration rate depends on the supply of water, the energy for evaporation and the pathway conductance (Kramer and Boyer, 1995). Transpiration rate can be calculated by the difference in vapor pressure between air and that of the leaf internal air space (VPD) and

stomatal conductance (transpiration  $\sim$  VPD\*stomatal conductance). Stomatal guard cells respond to the air humidity (atmospheric water vapor), leaf water condition, light availability and intensity, air temperature, air CO<sub>2</sub> concentration, and plant metabolite production (Farquhar and Sharkey, 1982). Thereby, tree water use varies over time and depends on environmental and weather conditions (Whitehead et al., 1996; Oren and Pataki, 2001; Tang et al., 2006; Mackay et al., 2007; Loranty et al., 2008; Heilman et al., 2009).

Air vapor pressure depends on relative humidity and temperature, while the leaf's vapor pressure depends on temperature and assumes full saturation of air in the internal leaf spaces. The vapor pressure deficit between air and leaf causes vapor to flow from leaf to atmosphere and it is maintained by energy inputs to the leaf. Energy input, generally by solar radiation, makes the vapor pressure of internal leaf spaces to be greater than the vapor pressure in atmosphere. Further, the evaporation gradient from plant surface is high when VPD is high and the transpiration rate may increase, the opposite will happen when VPD is low (Oren and Pataki, 2001).

Stomatal conductance is controlled by air water vapor combined with other factors as temperature, radiation, air movement, and soil water status. Plants exchange energy with the atmosphere through evaporation of moisture from plant surface and by absorption of solar radiation and/or reflected radiation (Kramer and Boyer, 1995). Plenty of solar radiation along with high air temperature will increase leaf temperature and can thus enhance transpiration rate due to higher VPD and stomatal conductance. Stomatal opening regulates transpiration while allowing the CO<sub>2</sub> exchange. A higher ambient CO<sub>2</sub> concentration would increase plant water use efficiency, due to reduction in needs of

stomatal conductance (Cech et al., 2003). Moreover, wind may affect transpiration in two different ways; it may increase transpiration by reducing leaf boundary layer resistance or decrease transpiration by cooling leaves. According to Kramer and Boyer (1995), increases in transpiration are mostly caused by low velocity winds. Although, under high radiation, low velocity winds may decrease transpiration on water-deficient leaves that are probably warmer than the surrounding air (Knoerr, 1967).

Low soil moisture decreases stomatal conductance and can reduce the response of transpiration to VPD (Oren and Pataki, 2001). Soil moisture is controlled by soil water input, i.e. precipitation, as well as soil depth and texture. In general, humid environments may have more water available to plants than in drier environments. In arid and semi-arid environments, winter precipitation may account for much of the soil water availability during spring and summer (West et al., 2007). The rate of soil water depletion is slower during winter than in summer because evaporative demand is lower under cooler conditions of winter (Schwinning and Sala, 2004). Depending on soil water content, hydraulic conductivity can be reduced by decreasing soil moisture (stomatal closure) and by xylem conduit cavitation. Xylem conduit cavitation occurs when the xylem water tension becomes so great that the water vaporizes and the air bubble breaks the sap column (Zimmermann, 1983). Cavitation may occur under lowered water availability and high transpiration rates and varies within species (Sperry et al., 1998).

In general, conifers possess lower water conductivity capacity than angiosperms (Farmer, 1918; Biffoss, 1947). Conifers have only tracheid cells, while angiosperms have both vessels and tracheid for water movement, but mainly use vessels that have larger diameter. Wullschleger et al. (1998) reported whole tree water use for numerous

hardwoods species from different studies; *Eucalyptus* sp. used a maximum of 285 liters of water/day, and some species of the *Populus* genera used from 50 to 109 liters of water/day. Several studies have been conducted to evaluate tree water uptake for different conifers. Simpson (2000) found a range of 1.8 to 166 liters day<sup>-1</sup> for Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco) trees of 7.5-70cm of diameter in an uneven age and irregularly spaced forest. Ponderosa pine (*Pinus ponderosa*) trees that average 37 and 13m of height used a maximum of 400 and 250 liters/day during summer (Williams et al., 2001). Moore et al. (2004) reported a max sap flow of 1750 and 750 liters/m<sup>2</sup> sapwood/day respectively for young (40 years) and old (400 years) *Pinus menziesii* trees in a riparian forest. Further, modeled maximum transpiration rate for western juniper (*Juniperus occidentalis*) was approximately 1728 l/m<sup>2</sup>/day in summer (Angell and Miller, 1994). Eddleman and Miller (1991) determined that a tree of the same species (*Juniperus occidentalis*) of 44 cm of basal diameter used a max of 132 liters/day on July and August, and 15 liters/day on November. In a year with lower soil moisture, however, the water use in July was 105 liters/day, and as low as 5 liters/day in January. Owens (1996) estimated that total water loss by *Juniperus ashei* can be high as 125 liters/day in mixed *Q. virginiana*- *J. ashei* communities in south-central Texas.

Beyond inter species variability, tree size and age change water use patterns. Younger stands are known to transport water more efficiently than older stands (Moore et al., 2004). This difference could be associated with the fact that increasing height will increase the hydraulic resistance due to lengthening of the pathway and an increase in the gravitational component of water potential (Ryan and Yoder, 1997). In addition, older trees show higher stomatal sensitivity to VPD (Moore et al., 2004; Tang et al., 2006).



However, bigger trees have larger DBH and often larger sapwood area which might increase total water use (Granier et al., 1996).

Larger trees may have more extensive root systems that increase access to deeper soil layers and increases water availability. Shallow rooted trees strongly reduce sap flux in response to VPD when the top soil layer gets dry. In contrast deeper rooted trees may slow their water use gradually as soil water decreases (Oren and Pataki, 2001). In addition, transpiration rate varies diurnally and seasonally according to the distribution of solar radiation within canopy layers. More dense stands have most of the canopy in a smaller single layer, overlapping each other and reducing light penetration. In comparison, less dense stands with close canopy are characterized by a uniformly vertical canopy profile. Granier (1987) found that suppressed trees, that are partially shaded and have smaller diameters, use less water per day compared with dominant trees.

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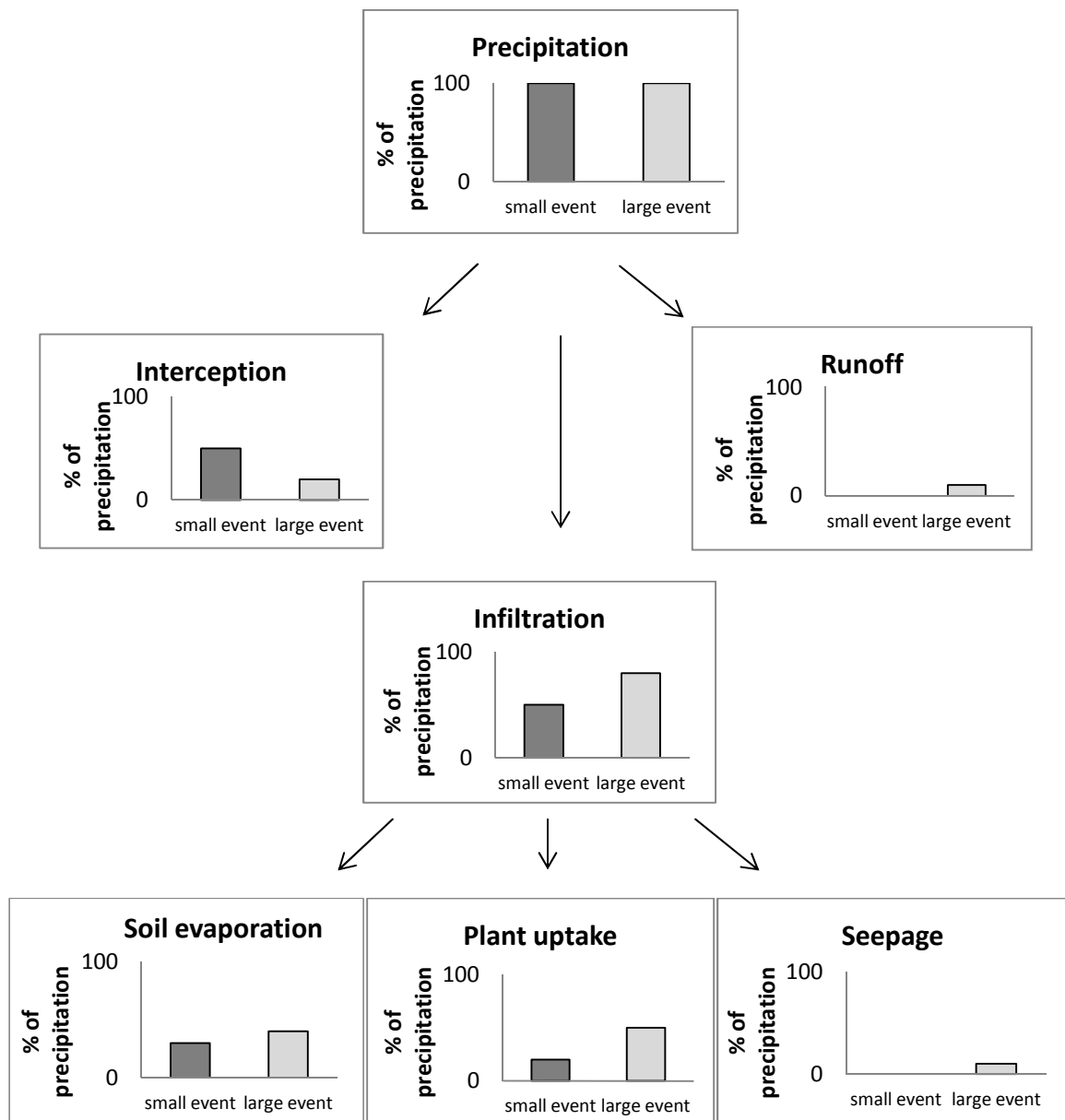
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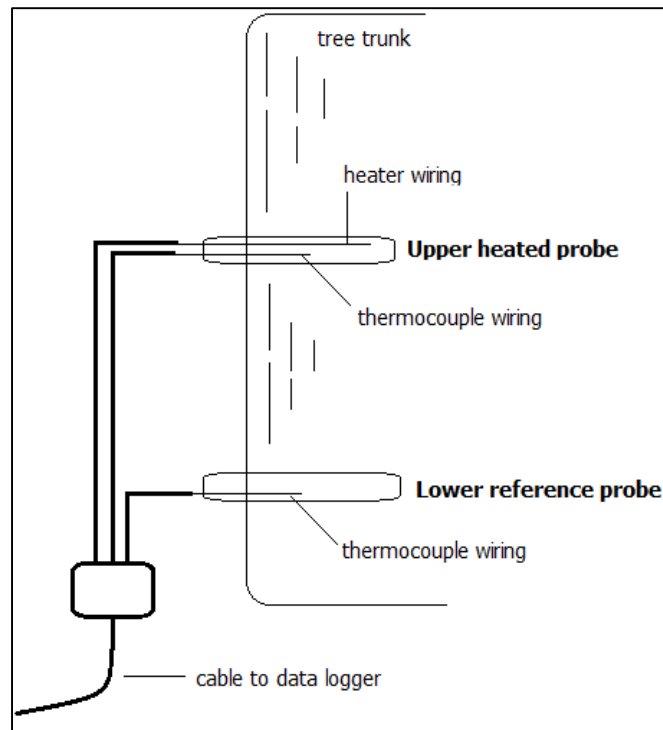
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**Figure1.** General percentage of each major component of the water budget generated after a small (<5 mm) and a large event (>30 mm). Seepage is the movement of water downward through the soil profile (source: Loik et al., 2004).



**Figure 2.** Schematic showing Granier thermal dissipation probes inserted into the tree trunk.



## CHAPTER II

Manuscript to be submitted to Hydrological Processes

### *JUNIPERUS VIRGINIANA* ENCROACHMENT INTO MESIC PRAIRIES: CANOPY INTERCEPTION

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#### Abstract

*Juniperus virginiana* (eastern redcedar) encroachment changes the biota, soil, and water budget of the Great Plains in the United States. To better predict the changes caused by this encroachment to grasslands water supply, it is necessary to quantify rainfall interception for *J. virginiana*. We measured *J. virginiana* throughfall, and stemflow, and analyzed which factors control them. We sampled *J. virginiana* trees of different diameters (from 6 to 47 cm DBH) and from different growth types (closed and open-grown). We also accounted for environmental factors that could influence canopy interception and stemflow variation, as well as rainfall amount,

intensity and duration, daily average wind speed, daily maximum wind gust, and daily potential evapotranspiration. *Juniiperus virginiana* average canopy interception was 37% of the total rainfall that occurred during 47 events. Throughfall was 80% of large rainfall events, and 0% during small events. Stemflow was generated in 34 rainfall events, representing an average of 7% of rainfall. Canopy interception amount increased as rainfall amount increased but was highly variable during the study period. Rainfall amount, intensity and duration were the factors that significantly explained throughfall. Throughfall increased with increasing rainfall amount, intensity and decreased with rainfall duration. Throughfall was not significantly correlated to tree diameter or growth type. Stemflow was positively related to event rainfall intensity, and negatively related to tree diameter.

**KEY WORDS:** eastern redcedar; throughfall; stemflow; interception

## INTRODUCTION

The encroachment of woody plants into grasslands is an economic and ecological issue worldwide. Replacing herbaceous species by woody species will result changes in a suite of biological, hydrological properties associated with grasslands and consequently alteration of grassland's water budget. *Juniperus virginiana* (eastern redcedar) is the most common woody invasive species in the mesic prairies of the eastern Great Plains in the United States (Fuhlendorf, 1999; Briggs et al., 2002b; Engle et al., 2007). The expansion of *J. virginiana* into the Great Plains is associated with overgrazing, fire suppression (Briggs et al., 2002a; Briggs et al., 2002b; Knapp et al., 2008), and this species' ability to adapt to different environmental conditions (Owensby, 1973; Owens, 2008). *Juniperus virginiana* encroachment is predicted to increase exponentially (Bidwell et al., 2002) and can lead to a complete loss of grassland in certain locations. In the state of Oklahoma, around 12.6 million acres of rangelands and grasslands are projected to be encroached (defined as areas with  $>124$  tree ha<sup>-1</sup>) with *J. virginiana* by 2013 (NRCS, 2008). The gender *Juniperus* sp. is invading Texas, Kansas and Nebraska at a similar rate (Knapp et al., 2008).

Woody plant encroachment into grasslands impacts an ecosystem's vertical and horizontal water distribution (Owens et al., 2006). The vertical distribution of rainfall is first determined by vegetation canopy interception. Canopy interception determines the amount of rainfall that will reach the soil (Loik et al., 2004). Canopy interception depends on a specie's canopy storage capacity and the amount of water that a vegetation canopy can hold (Horton, 1919). The water held by the canopy can either drip from the

vegetation surface, when storage capacity is exceeded, or be evaporated back to the atmosphere.

Canopy interception can be major loss of water from ecosystems. According to a literature review of studies in different regions done by Carlyle-Moses (2004), coniferous forest canopies intercept an average of 26% of rainfall. Arid and semiarid ecosystems typically intercept most of the rainfall in events between 2 and 5 mm (Loik et al., 2004). Due to the high potential of *J. virginiana* to intercept precipitation, encroachment may decrease water distribution for transpiration and soil water recharge. In research conducted in the Edwards Plateau in central Texas, *Juniperus ashei* Buchholz (Ashe juniper) average canopy interception was found to be 40% while the stemflow was about 5% of rainfall (Owens et al., 2006). From the same study, rainfall events less than 2.5 mm were totally intercepted by Ashe juniper trees. However, *J. virginiana* interception in north-central Oklahoma should differ from Owens et al. (2006) results. Even though *J. virginiana* and Ashe juniper have similar canopy structure, they are located in different environments. Therefore, it is necessary to directly measure *J. virginiana* canopy interception in this region.

Canopy interception is an important component of a watershed's water budget. Our objectives were to directly quantify *J. virginiana* throughfall and stemflow, and determine which tree characteristics (size and canopy openness) and meteorological variables (rainfall amount, intensity and duration, wind speed, and potential evapotranspiration) control them.

## METHODS

The research was performed at the Cross Timbers Experimental Range (CTER), a 728 ha research and extension facility under the administration of Oklahoma Agricultural Experiment Station of Oklahoma State University. This site is located about 11 km southwest of Stillwater in Payne County, Oklahoma (36°04"N, 97°21"W) (Engle et al., 2006). The climate is continental with a growing season of 204 days on average. The average annual precipitation is 942 mm with 65% occurring from May to October. Average daily temperatures range from a minimum of -4.3°C in January to a maximum of 34°C in August. The annual daily average is 15°C (Oklahoma Annual Climate Summary, 2002). The CTER site consists of eastern deciduous forests, savanna, and tallgrass prairie (Ewing et al., 1984). *Juniperus virginiana* has invaded the tallgrass prairie areas with intensities ranging from 10% to almost 100%.

Three sites with different *J. virginiana* trees growth patterns (open or closed grown) and canopy coverages were selected from encroached sites: 1. An open grown site (OG) consisted of widely spaced trees with live branches growing all along the stem, 2. A closed grown site (CG) had 100% encroachment with trees characterized by live branches growing only on the upper trunk, 3. A transitional site (HG) that contained patches of both open- grown trees (HG<sub>o</sub>) and closed-grown trees (HG<sub>c</sub>).

Canopy interception ( $I_c$ ) was determined by:

$$I_c = P - T - S \quad (1)$$

where P is rainfall, T is throughfall, and S is stemflow.

Net precipitation ( $P_n$ ), the water that reaches the soil surface after falling through the canopy, was determined by:

$$P_n = P - I_c \quad (1)$$

To measure throughfall and stemflow 25 trees were selected, 5 at the OG site and 10 at each of the CG and HG sites. Tree diameters were representative of the range of diameter classes measured during an inventory of the sites.

Both precipitation and throughfall were measured using 103 mm diameter acrylic rain gauges that had a capacity of 365 mm. Gross precipitation was collected using two tipping bucket rain gauges, one located near the OG site, and the other near the CG site. Both tipping bucket rain gauges were placed in an open area where a clear view of 45° from the gauge edge was possible, to prevent turbulence and eddy currents caused by trees (Helvey and Patric, 1965). To capture throughfall, 8 rain gauges were randomly located under each of the 25 trees (200 in total). Each gage was randomly located using a random distance from the trunk and random compass azimuth. The number of rain gauges under each tree canopy was chosen based on previous study (unpublished data). Stemflow was collected by a metal collar placed around each selected tree (25 in total). The metal collars were sealed to the tree trunk and connected by a PVC pipe to two 144 liter capacity reservoirs. To convert stemflow volumes to depth (mm), the volume collected in the reservoirs was divided by the respective tree canopy area (m<sup>2</sup>). Rainfall, throughfall and stemflow were measured during the calendar year of 2011, and also two rainfall events at the end of 2010 and two at beginning of 2012. Precipitation and throughfall data were collected from 47 events. Measureable stemflow was generated by 34 of the 47 events. An event was defined as a period of measurable rainfall separated

by at least five hours with no rain. A break point of 5 h was chosen because it took that much time to collect the data from all of the throughfall cans and stemflow collectors. Rainfall intensity and duration, daily average wind speed, daily maximum wind gust, and daily potential evapotranspiration were measured at a meteorological station located nearby (< 0.5 km) to identify which meteorological factors affect canopy interception. The meteorological data was collected by a Campbell Scientific Instruments CR1000 data logger at 5 minute intervals.

Data was analyzed using SAS statistical software (SAS 9.3, SAS Institute, Cary, NC). Analysis of variance (ANOVA) was used to analyze the relationships between throughfall, stemflow, canopy interception and net precipitation and rainfall amount. A null model was conducted using PROC MIXED to determine the association between the variability in throughfall and stemflow and random factors (tree diameter, site, and rainfall amount). Then, a full model was used to determine how the independent factors (growth form, rainfall intensity and duration, max wind speed, max wind gust, and potential evapotranspiration) affected throughfall and stemflow. In the mixed model, we used the log of the dependent factors (throughfall and stemflow), rainfall amount and intensity, and max wind speed to normalize the data.

## RESULTS

The 25 *J. virginiana* trees averaged 190 mm ( $\pm$  24 mm s.e.) in DBH (diameter at breast height  $\sim$  1.37m) and the canopies areas averaged 21 m<sup>2</sup> ( $\pm$  3.7 m<sup>2</sup> s.e.) (Table I).

During the study period, the total rainfall measured during 47 events was 664 mm. There were 18 events less than 5 mm and ten events greater than 25 mm. The largest event had 53 mm, and an event of 37 mm had the highest intensity of 46 mm h<sup>-1</sup>.

Total average (of all gages per event) throughfall ranged from 49.1 to 64.0%, and total average (of all collectors per event) stemflow ranged from 5.2 to 10.5% of rainfall (Table II). Interception averaged (all gages, all events) 36.9% ( $\pm 2.05$  s.e.) of rainfall. The relationships between the event rainfall and throughfall, stemflow and canopy interception expressed as a percent of rainfall, are shown in Figure 1. As rainfall amount increased, the throughfall and stemflow percentages of rainfall increased exponentially until reaching approximately constant values, while canopy interception percentages of rainfall declined exponentially.

Net precipitation increased linearly with rainfall amount, and occurred when rainfall was greater than 1.54 mm (Figure 2). As event rainfall increased, event throughfall (Figure 3) and stemflow (Figure 4) increased linearly. Throughfall occurred when rainfall was greater than 1.44 mm (Figure 3), and stemflow, when rainfall was greater 2.25 mm (Figures 4). Throughfall and stemflow were also dependent on other factors. Rainfall event characteristic was the main random factor that explained throughfall. Testing throughfall, the sources of variation with equivalent variance component (significant at  $p \leq 0.05$ ) were growth type (0.0052,  $p = 0.250$ ), tree diameter (0.0262,  $p = 0.001$ ), rainfall event (2.7036,  $p < 0.0001$ ), residual (0.0574,  $p < 0.0001$ ). When growth type was dropped out of, and rainfall event characteristics were applied to the model, sources of variation and equivalent variance component were tree diameter



(0.0268,  $P = 0.0016$ ), rainfall event (0.1620,  $P < 0.0001$ ), and residual (0.0512,  $P < 0.0001$ ). The model that predicts throughfall (with variables significant at  $P \leq 0.05$ ) was:

$$\log_{\text{throughfall}} = -1.3006 + 1.1914 \log_{\text{rainfall amount}} + 0.1136 \log_{\text{rainfall intensity}} - 0.03088 \text{ rainfall duration}$$

Rainfall event characteristics and tree diameter were the main random factors that explained stemflow. Testing stemflow, the sources of variation and equivalent variance component (significant at  $p \leq 0.05$ ) were growth type (0.0081,  $p = 0.3875$ ), tree diameter (0.1443,  $p = 0.0012$ ), rainfall event (1.4928,  $p < 0.0001$ ), residual (0.2592,  $p < 0.0001$ ). When growth type was dropped out of the model, and rainfall event characteristics were applied, sources of variation and equivalent variance component were tree (0.0964,  $p = 0.0019$ ), rainfall event (0.1566,  $p < 0.0001$ ), and residual (0.2640,  $p < 0.0001$ ). The model that predicts stemflow (with variables significant at  $p \leq 0.05$ ) was:

$$\log_{\text{stemflow}} = -1.973 - 0.0185 \text{ tree diameter} + 0.775 \log_{\text{rainfall amount}} + 0.0937 \log_{\text{rainfall intensity}}$$

## DISCUSSION

A study in the semiarid Edwards plateau in south-central Texas showed that about 35% of the rainfall falling on *J. ashei* was intercepted by the tree canopy (Owens et al. 2006). Young et al. (1984) determined that canopy interception was 42% of rainfall in *J. occidentalis* stands located in western Lassen County, California. These studies

highlighted the high percentage of interception water loss associated with juniper species. We found that *J. virginiana* canopy intercepted an average of 37% of the total precipitation.

Amount, intensity and duration of precipitation, and wind velocity, and evaporative demand are some of the storm characteristics that influence the interception process (Breshears et al., 1998; Brooks et al., 2003; Owens et al., 2006). Our results showed that only precipitation intensity, duration and amount significantly affected canopy interception. Smaller events were almost completely intercepted by the *J. virginiana* canopies (Figure 1). This outcome from the relationship between interception and event rainfall is in substantial agreement with the findings of Owens et al. (2006). During the study, rainfall was below normal and was characterized by events of low intensity and short duration. This could explain the relatively large percentages of rainfall intercepted (Table II). During this study, 18 of the event rainfalls were <5 mm, and only 10 were  $\geq 25$  mm. Events < 5mm accounted for 6 % of total rainfall, and 12 % of total canopy interception, while events  $\geq 25$  mm account to 59% of rainfall and 51% of canopy interception (Table III). Small events contributed to small portions of rainfall amount but proportionally high portions of canopy interception.

The variations in throughfall and stemflow amounts were mostly explained by rainfall event characteristics. Both increased as event rainfall and intensity increased. Throughfall amount was found not to be function of tree diameter or growth type. This occurrence may be explained by the fact that the rainfall events were mostly small and of low intensity. Low amounts with low intensity rainfalls would lead to higher amounts held by the canopy independent of canopy size.

Stemflow can range from less than 2% (Brooks et al., 2003) to over 8% (Carlyle-Moses, 2004) of rainfall, depending on the species and rainfall intensity. In our study the stemflow averaged 7% of rainfall. Stemflow occurred on average when event rainfall was greater than 2.25 mm. This can be explained by the fact that small, low intensity storms may be completely absorbed by the bark of *J. virginiana*. This species usually has thick and porous bark that requires plenty of water to saturate it. Stemflow amounts were found not to be a function of the growth type. A small portion of stemflow amounts were affected negatively by tree diameter. Larger trees have bigger and more porous bark, what increase the capacity of water absorption before it flows along the trunk as stemflow, especially during small rainfall events as the majority of the events on this study. Most of the stemflow amounts were positively affected by rainfall amounts and intensities. Tree bark will saturate quickly during larger and more intense rainfall events, which would lead to larger stemflow amounts. In addition, as more water falls as rainfall, more water flows along the tree trunk. A relatively large part of stemflow variation could not be explained by our random variables.

*Juniperus virginiana* decreased net precipitation by 37%. Depending on the method of measurement and on the species under consideration, litter interception can significantly decrease net precipitation (Thurrow et al., 1987; Silva and Rodriguez, 2001; Carlyle-Moses, 2004; Linneman and Palmer, 2006). Owens et al. (2006) found that, 5% of total rainfall was intercepted by *J. ashei* litter. Our interception results were based only on the measurement of the throughfall and stemflow, and we acknowledge that it is necessary to include litter interception in the calculation of net precipitation. The litter produced by the *J. virginiana* trees is thick, continuous, and decomposes slowly (Norris

et al., 2001). However, some studies have shown that litter interception and stemflow are usually equal in percentage of event rainfall, which may result in no effects on net precipitation, regardless canopy interception (Owens et al. 2006). In that case, net precipitation can be considered to be equal to throughfall.

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Table I. Characteristics of all *J. virginiana* trees used to measure canopy interception in encroached mesic tallgrass prairie watersheds. OG = open grown site, HO= hybrid open site, HC hybrid closed site, CG= closed site, EC= closed site 2. DBH is the diameter at breast height (~1.37 m).

Tree ID	Growth type	DBH (cm)	Canopy area (m <sup>2</sup> )
OG1	open	6	9
OG2	open	13	17
OG3	open	22	31
OG4	open	29	53
OG5	open	36	49
HO1	open	6	7
HO2	open	8	9
HO3	open	15	26
HO4	open	23	27
HO5	open	45	75
HC1	closed	6	4
HC2	closed	11	5
HC3	closed	16	12
HC4	closed	22	14
HC5	closed	23	18
CG1	closed	6	3
CG2	closed	12	9
CG3	closed	18	17
CG4	closed	25	21
CG5	closed	47	48
EC1	closed	6	3
EC2	closed	13	10
EC3	closed	21	17
EC4	closed	26	30
EC5	closed	34	41

Table II. Total throughfall, stemflow, and canopy interception averages and standard errors for the study period expressed as a % of rainfall. OG = open grown site, HO= hybrid open site, HC hybrid closed site, CG= closed site, EC= closed site 2.

Site	% of Rainfall		
	Throughfall	Stemflow	Canopy interception
OG	64.0 $\pm$ 3.30	6.4 $\pm$ 1.59	29.6 $\pm$ 3.86
HO	58.1 $\pm$ 4.13	6.6 $\pm$ 2.25	35.3 $\pm$ 2.43
HC	49.1 $\pm$ 3.82	10.5 $\pm$ 1.44	40.4 $\pm$ 4.45
CG	54.3 $\pm$ 3.69	5.2 $\pm$ 1.04	40.5 $\pm$ 4.24
EC	56.1 $\pm$ 4.47	5.3 $\pm$ 0.87	38.6 $\pm$ 4.10



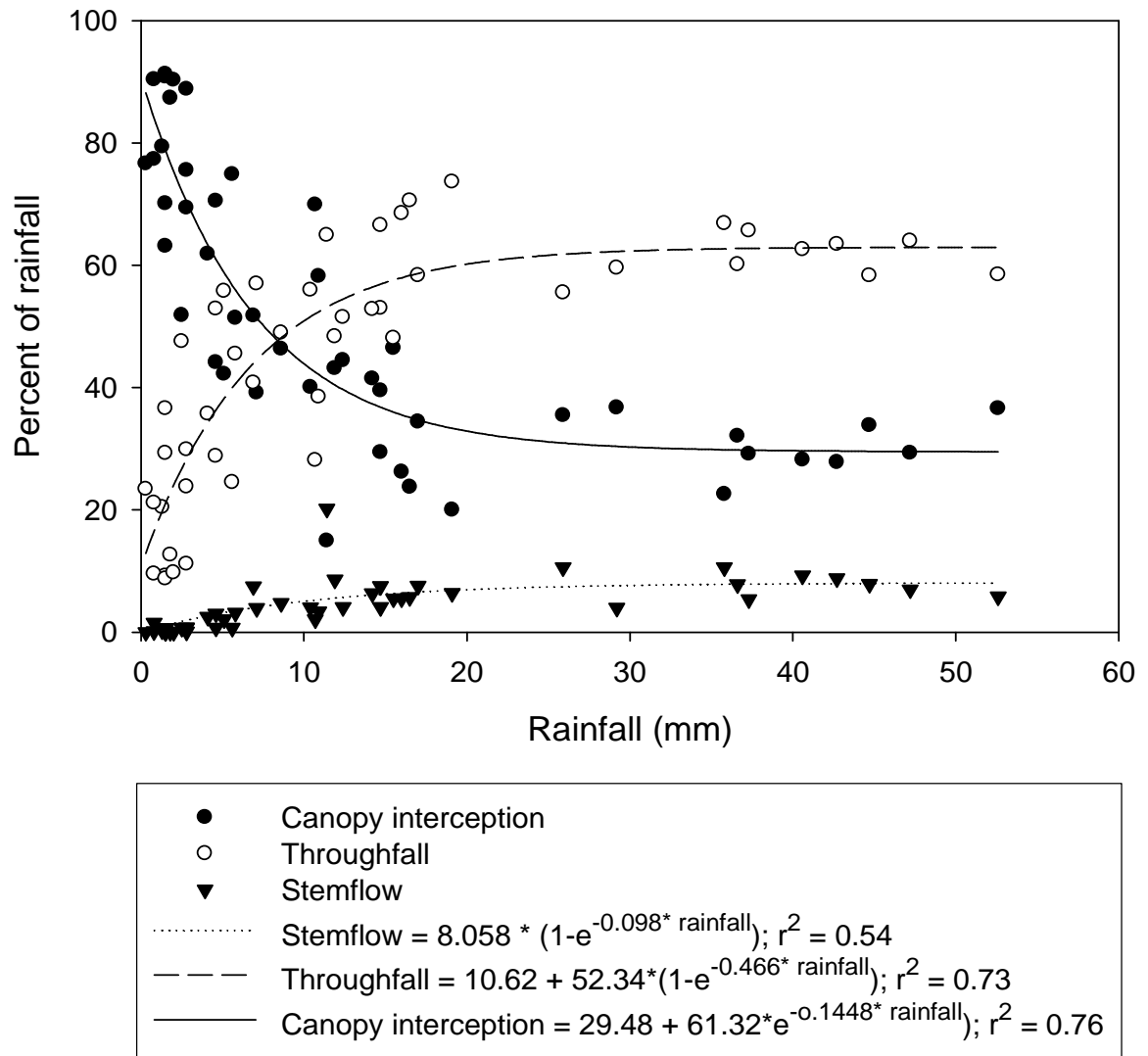


Figure 1. Variation of throughfall, stemflow, and canopy interception of *J. virginiana* trees (n = 25) expressed as % of rainfall under different event rainfall sizes (n = 47).

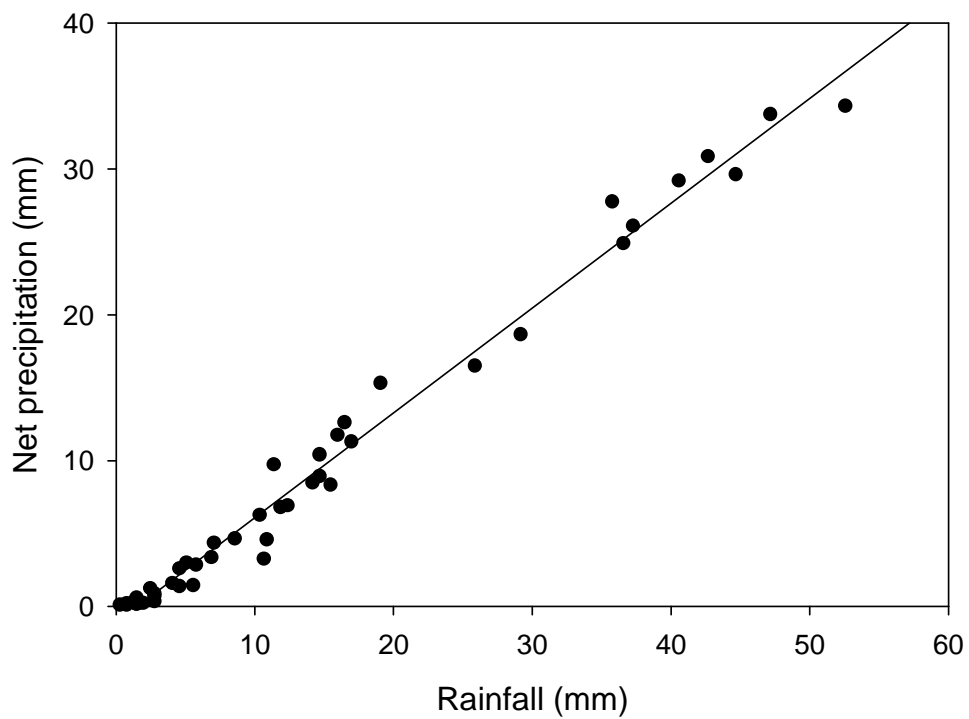


Figure 2. Event average net precipitation ( $P_n$ ) vs. event rainfall ( $P$ ). The linear relationship is represented by the equation:  $P_n \text{ (mm)} = -1.10216 + 0.71886 * P \text{ (mm)}$  ( $r^2 = 0.97$ ,  $p < 0.05$ ).

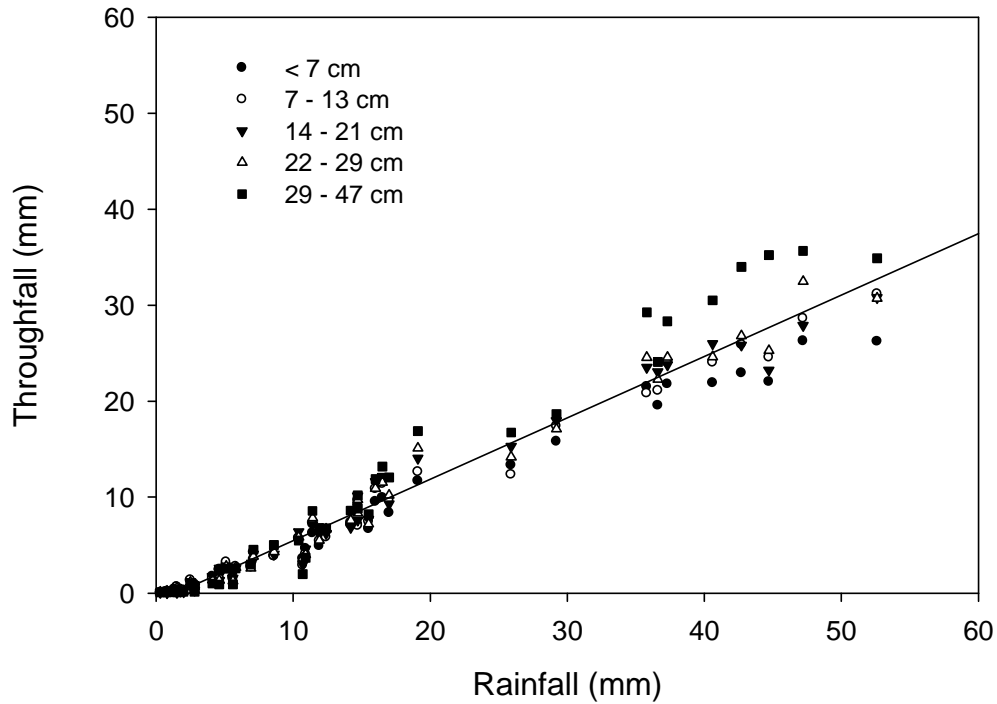


Figura 3. Event average throughfall for *J. virginiana* vs. event rainfall (P). The linear relationship is represented by the equation:  $\text{Throughfall (mm)} = -0.90746 + 0.63562 \cdot P$  (mm) ( $r^2 = 0.92$ ,  $p < 0.05$ ). DBH classes are separated with different markers. DBH is the diameter at Breast Height (~1.37 cm).

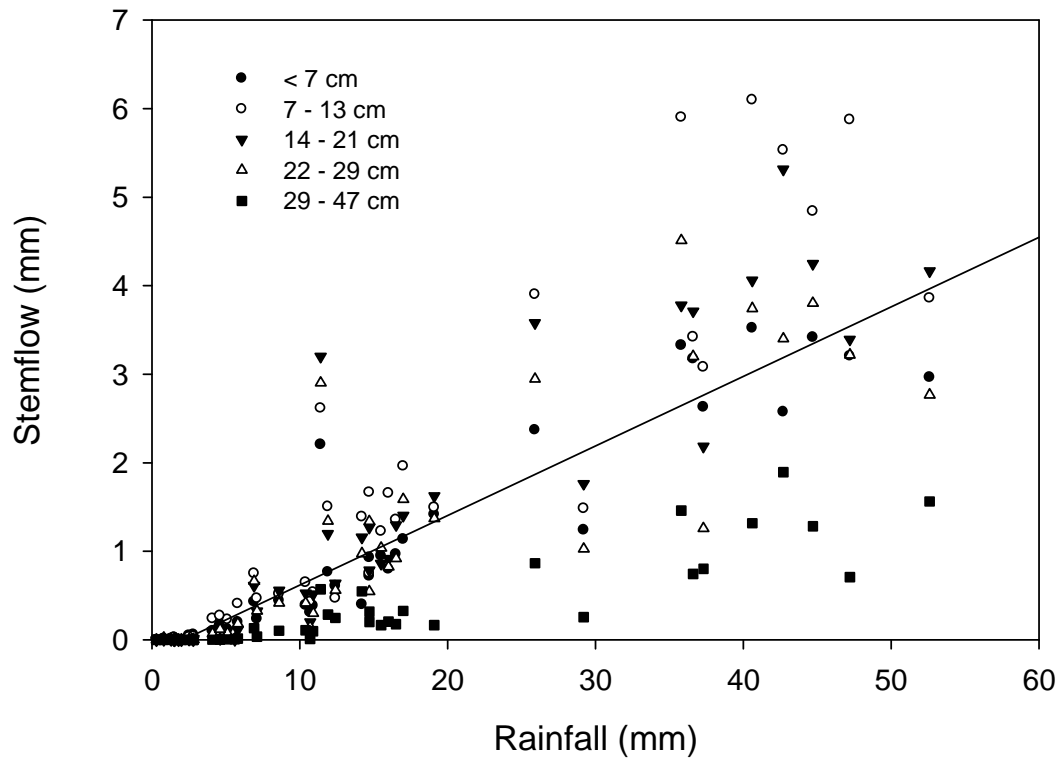


Figura 4. Event average stemflow for *J. virginiana* vs. event rainfall (P). The linear relationship is represented by the equation: Stemflow (mm) = -0.17206 + 0.08088\*P (mm) ( $r^2 = 0.50$ ,  $p < 0.05$ ). DBH classes are separated with different markers. DBH is the diameter at Breast Height (~1.37 cm).

Table III. Distribution of rainfall event sizes that occurred during the study period of 15 months between December 2010 and February 2012 by event size class, the number of events in each class and the percent of the accumulated rainfall and canopy interception in each class.

Event rainfall (mm)	Number of Events	% of Total P	% of Total Ic
$\leq 5$	18	6	12
5 - 10	5	5	7
10 - 25	14	30	30
$\geq 25$	10	59	51

## CHAPTER III

Manuscript to be submitted to Tree Physiology

### WATER USE OF *JUNIPERUS VIRGINIANA* TREES ENCROACHED INTO MESIC PRAIRIES

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## Summary

*Juniperus virginiana* (eastern redcedar) is encroaching into mesic prairies of the south-central Great Plains of the United States at an alarming rate. To understand the effects this invasion has on ecosystem water budgets, it is important to quantify the water use by *J. virginiana*. We used the thermal dissipation technique to quantify *J. virginiana* daily water use of 19 trees of different size from low and high density stands located in north-central Oklahoma during 2011. The technique was calibrated to increase accuracy by comparing actual water use of cut trees to probe-based measurements. *Juniperus virginiana* trees used water year-round reaching a peak in late May and exhibiting reduced water use in summer time when conditions were dry. Overall daily average water use was 27 liters ( $\pm 5.5$  liters s.e.). Large trees transpired greater amounts of water than smaller trees, ranging from a 24-hour maximum of 4 liters (2cm diameter at breast height) to 150 liters (31cm diameter at breast height). Trees from low density stands used more water than trees with similar diameters from denser stands. However, there was no difference in water use between the two types of locations on a canopy area basis. Approximately two-thirds of the day-to-day variation in water use was explained using a functional equation that included daily potential evapotranspiration, vapor pressure deficit, maximum temperature, solar radiation, and volumetric soil water content between 0-10 cm. When scaled to a hectare basis, *J. virginiana* used most of the effective precipitation, indicating potential for encroachment to reduce water yield such as streamflow and groundwater recharge.

*Keywords: Eastern redcedar, transpiration, sap flow, Granier sensors*

## Introduction

Grasslands are being encroached by woody plants worldwide (Archer et al. 2001, Van Auken 2000), which potentially causes substantial change in the biogeochemical and hydrological cycles of these important grassland ecosystems (Engle et al. 2007, Knapp et al. 2008). *Juniperus virginiana* (eastern redcedar) is the primary species encroaching into the mesic prairies of the south central United States. In north-central Oklahoma, the area encroached by *J. virginiana* is projected to reach 12.6 million acres by 2013 (NRCS 2010). Given the large scope of the affected area, *J. virginiana* encroachment may have a large impact on the regional water budget.

The replacement of C<sub>4</sub> grasses by the evergreen, C<sub>3</sub> redcedar dramatically changes the seasonal dynamics of growth and photosynthesis and thereby plant water use pattern. *Juniperus virginiana* is phenologically active year round compared to five months for grasses (Knapp et al. 2008). *Juniperus virginiana* woodlands annually produce from two to three times more aboveground biomass than C<sub>4</sub> grasslands and accumulate more than 20x the aboveground standing biomass (Briggs and Knapp 1995, Lett et al. 2004, Norris et al. 2001). *Juniperus virginiana* is drought tolerant, and it is able open stomata at lower soil water potentials and has high water use efficiency (Eggemeyer et al. 2006, Willson and Jackson 2006). Additionally, juniper species generally have deeper rooting systems which are able to access water at depths unavailable to grasses (Huxman et al. 2005, Tennesen 2008). *Juniperus virginiana* exhibits flexibility by exploiting water from deeper soils in winter and from the upper soil in spring when shallow water is available (Eggemeyer et al. 2008).



Measurements of plant water use are required for an accurate estimation of the water balance within an ecosystem. Evapotranspiration, which includes evaporation from soil and plant surfaces and transpiration from plant stomata (Wilcox et al. 2003), is usually the largest component of the water budget in an ecosystem. For most ecosystems, transpiration is the dominant process controlling plant water relations and this process extracts a huge amount of water from soil and releases it into atmosphere through soil-plant-atmosphere continuum (Kramer and Boyer 1995). Over time, the transpiration rate from a forest can be four times higher than evaporation from bare soil (Brooks et al. 2003). Because of its importance, several techniques have been developed to estimate plant transpiration. Some methods are based on an energy balance approach (Berbigier et al. 1996, Bowen 1926, Mackay et al. 2007, Moore et al. 2008, Tang et al. 2006), but these methods have high uncertainty in partitioning estimated evapotranspiration into evaporation and transpiration (Wullschleger et al. 1998). Several methods are based on measuring transpiration directly. Among those, the heat dissipation technique is commonly used, due to its relatively low costs, simplicity, and automation (Wullschleger et al. 1998). This technique measures the ascent of sap near the base of the trunk for a given tree and assumes that it is equivalent to transpiration (Smith and Allen 1996).

Sap flow measurements of individual trees can be scaled to the stand level if the water use of a range of sample trees that represent both the size and age distribution and growth type of the population of interest can be experimentally quantified (Čermák et al. 2004). An easy to measure variable to extend the values of individual tree water use to the entire stand using regression models facilitate the scaling process (Wullschleger et al. 1998). This variable could be stem diameter at breast height (DBH) (Vertessy et al.

1995), basal area (Teskey and Sheriff 1996), crown or leaf area (Hatton et al. 1995), or sapwood area (Dunn and Connor 1993). Transpiration rate responds quickly to environmental conditions, and the relationship between water use and a tree variable used to predict water use may be temporally unstable over short-term intervals (Hatton et al. 1995). Measurement of water use over long periods representing all different seasons and weather conditions are necessary to make water use extrapolations on annual basis.

Plants water use varies depending on weather conditions, environmental conditions, and species-specific characteristics (Farmer 1918, Heilman et al. 2009, Loranty et al. 2008, Oren and Pataki 2001, Tang et al. 2006). Determining *J. virginiana* water use in a mesic prairie will provide a better understanding of the changes in this ecosystem's water balance due to encroachment. Our objective was to quantify the water uptake by individual *J. virginiana* trees in encroached watershed by measuring sap flow density (water/cm<sup>2</sup> of sapwood per hour) using thermal dissipation probes (TDP) described by Granier (1985). The probes were installed in trees of different diameters and growth type (open and closed grown) from low and high density stands located in north-central Oklahoma. To get specific empirical parameters, the technique was calibrated to *J. virginiana* by comparing actual water use of cut trees to sensor-based estimates of water use. We also measured daily meteorological variables to generate prediction models to help determine how weather affects *J. virginiana* water use and to scale our results from individual trees to the whole watersheds. These findings will be critical to evaluate the change in the water yield between encroached and intact tallgrass prairie watersheds.

## Materials and methods

### *Study area description*

The research was conducted at the Cross Timbers Experimental Range (CTER), a 728 ha research and extension facility under the administration of Oklahoma Agricultural Experiment Station of Oklahoma State University. This site is located about 11 km southwest of Stillwater in Payne County, Oklahoma (36°04'N, 97°21'W) (Engle et al. 2006). The climate is continental with a growing season average of 204 days. The annual precipitation average is 942mm with 65% occurring from May to October. The temperature ranges from an average daily minimum of -4.3°C in January to an average daily maximum of 34°C in August, and the annual daily average is 15°C (Oklahoma Annual Climate Summary, 2002). The CTER site is composed of cross timbers forest, savanna, and tallgrass prairie. The cross timbers area is dominated by hardwood species, such as post oak (*Quercus stellata*), blackjack oak (*Quercus marilandica*) in the overstory, and hackberry (*Celtis occidentalis*), American elm (*Ulmus americana*), and blackberry (*Rubus* spp.) in the understory. Dominant herbaceous species in the savanna and prairie areas are little bluestem (*Schizachyrium scoparium*), Indian grass (*Sorghastrum nutans*), western ragweed (*Ambrosia psilostachya*), Scribner's panicum (*Panicum oligosanthos* Schult.), purpletop (*Tridens flavus* L. Hitchc.), and lespedeza (*Lespedeza* spp.) (Ewing et al. 1984). *Juniperus virginiana* has invaded portions of the tallgrass prairie areas and there are different stages of forest formation with canopy coverage ranging from 10% to almost 100%.

Three sites of different redcedar growth patterns and canopy coverage were selected from the encroached tallgrass prairie areas at CTER. Trees in the "OG" site had

an open grown pattern that consisted of widely spaced trees with branches growing all along the stem, the “CG” site had closed grown pattern trees that were characterized by a closed canopy with branches growing only on the upper trunk, and the “Hybrid” site was a transition between open to closed forest and contained a mix tree growth forms.

Nineteen trees of a range of diameters were selected, totaling five trees at the OG site, six at the CG site and eight at the Hybrid with four each of open and closed growth form (HO, HC) (Table 1). The diameters selected represented the full range of the diameter distribution, based on an inventory, to ensure that they were representative of stems across the watershed.

#### *Environmental data*

To relate water use to environmental conditions, meteorological variables were measured at a weather station located approximately 60, 160 and 400 m from OG, CG, and Hybrid sites, respectively. The station measured: air temperature and relative humidity at 2 m, wind speed and direction at 3 m, solar radiation, soil temperature at 5 cm, and precipitation (siphoning tipping bucket rain gauge with a 0.254 mm tip). The data were recorded at 5 minute intervals and daily averages were calculated. Total potential ET (evapotranspiration, mm) was calculated based on air temperature, relative humidity, wind speed, and solar radiation using the standardized reference evapotranspiration equation (ASCE 2002). From February through April, ET was calculated based on a “shortgrass” reference. From May onward, ET was calculated based on a “tallgrass” reference. In addition, soil moisture was measured every 30 min during the project period and daily averages were calculated. Volumetric soil water

content ( $\text{m}^3/\text{m}^3$ ) was measured with ECH<sub>2</sub>O 5TE (Decagon Devices, Inc., Pullman, USA) sensors at depths of 5, 25, 50, 75, and 80 cm. The cumulative volumetric soil water content (VWC) was calculated for each soil profile section (0-10, 10-30, 30-60, 60-100 cm). Each site was equipped with 3 soil moisture stations located within an approximately 90, 45, 60 m from OG, CG, and Hybrid sites trees, respectively.

### *Water uptake*

The sap flow density was measured using thermal dissipation probes of 2 mm diameter and 10 mm or 30 mm in length (TDP-10 and TDP-30, Dynamax, Houston, TX). One set of 10 mm probes was used in trees with  $\leq 5$  cm of DBH. Two or three sets of probes, with at least one set of each length, were used in trees with diameters  $>5$  cm. The use of probes with different lengths in trees with  $>5$  cm diameter was to account for possible variation in xylem radial and axial water movement. The probes were placed approximately 1 to 2 m from the ground and bellow all live branches. There were times that they were placed at less than 1 m in height when live branches of open grown trees were near ground level. All probes were inserted in December of 2010 and sap flux was measured for a period of thirteen months.

Sap flow density was measured by a pair of sensors inserted radially into the tree trunk 40mm vertically apart from each other; the upper needle had a constant heater and a thermocouple. The lower probe had just a thermocouple. As the water moves up, it dissipates the heat generated by the upper needle. The faster water moves, the lower the temperature differential ( $\Delta T$ ) between the two needles. The temperature differential is maximum ( $\Delta T_{\text{max}}$ ) with minimal or no flow. The temperature differential between the

needles was measured every minute and the hourly mean was calculated and recorded by a data logger (CR10X, Campbell Scientific, Logan USA). According to Granier (1985, 1987a, 1987b), the sap flux density is highly correlated to a dimensional parameter ( $K$ ) which is determined by the  $\Delta T_{\max}$  and  $\Delta T$ :

$$K = (\Delta T_{\max} - \Delta T) / \Delta T \quad (\text{equation 1})$$

Sap flow velocity ( $V$ ) is calculated using the exponential equation:

$$V = 0.0119 * K^{1.231} \text{ (cm s}^{-1}\text{)} \quad (\text{equation 2})$$

Finally, sap flow density ( $F_s$ ) is calculated using both the sap flow velocity and the sapwood area ( $SA$ ) in  $\text{cm}^2$ :

$$F_s = SA * V * 3600 \text{ (cm}^3 \text{ h}^{-1}\text{)} \quad (\text{equation 3})$$

To measure the sapwood area, the trees were cut down at the end of the study in March of 2012. A trunk cross-section at the height where the probes were inserted was drawn on a piece of paper. Because of the difference in color between the sapwood (white) and heartwood (red), it was possible to accurately distinguish sapwood from heartwood. The paper that represented sapwood area was then measured with a LI-3000 leaf area meter (LI-COR Inc., Lincoln, NE). Tree height, canopy dimensions, and DBH were also measured at time of harvest. Dry foliage biomass for each tree was calculated with prediction equations described by Lykins (1995).

### *Calibration*

Two different methods were used to calibrate the TDP technique to *J. virginiana* trees in our study. The first calibration experiment was conducted between August and September of 2011. For this method, trees were selected within the study area. The nine chosen trees ( $8 \text{ cm DBH} \pm 0.77 \text{ cm s.e.}$ ), were cut as close to the ground as possible and then placed immediately in buckets filled with water to avoid the embolism of the tracheids. Trees were then placed and secured in large, fully filled water reservoirs ( $\sim 100 \text{ l}$ ). Extra probes were used for this calibration; 30mm and 10mm deep probes were inserted in opposite directions in each tree. Each hour for 10 hours during day-light, water was added from a graduated cylinder to fully refill the reservoir and actual water use was calculated. Sapwood area of each tree was measured using the methods outlined above.

The second calibration was conducted in March of 2012. This time, five trees ( $9 \text{ cm DBH} \pm 2.55 \text{ cm s.e.}$ ) from the sap flow experiment were used. The methodology consisted of measuring the actual tree's hourly water use by cutting entirely through the sapwood around the tree trunk and placing a bucket filled with water around the tree below the incision. To put the bucket around the tree, the bucket was cut cross-wise into top and bottom sections and then taped with waterproof tape. The bottom section of the bucket was set below the location of the cut and sealed to the tree using expanding urethane foam. The top part of the bucket was placed on the bottom section and sealed with waterproof tape at 0800 and filled with water within 10 min after cutting, to minimize tracheid embolism. The buckets were refilled with a graduated cylinder every hour during a period of 10 hours starting at 0900. Sapwood area was calculated after the trees were cut down. For both experiments an additional cut around the tree trunk through

the sapwood above the probes was conducted at sunset to prevent any additional water movement and to accurately determine  $\Delta T_{\max}$ .

Tree water use values calculated using the standard Granier equation and the TDP probe data were calibrated using the actual water use based on water additions to the reservoirs. Estimated and empirical cumulative 10 hour water use were divided by the tree's sapwood area and a linear regression was used to determine the correction equation (Sun et al. 2012) (Figure 1).

### *Sap flux data analyses*

Daily water use (each 24 hour period) was calculated for the 2011 calendar year by summing hourly observations and then applying the appropriate calibration equation for each sensor length. Data were analyzed with SAS statistical software (SAS 9.3, SAS Institute, Cary, NC). The effects of growth form on the relationship between DBH and canopy area and sap flux were tested using the interaction between growth forms. Transpiration is determined by the atmospheric driving force (VPD) and stomatal conductance as influenced by soil water availability. VPD also directly influences stomatal conductance (stomata close as VPD increases). In addition, stomatal conductance increases with solar radiation and is greatest under moderate temperature (Lloyd et al. 1995). To test for and explain the effects of weather and soil water on daily water use, a functional equation was developed that was analogous to Darcy's law that accounted for atmospheric demand (potential evapotranspiration during daylight) and factors that affect stomatal conductance (VPD, maximum temperature, and daily solar radiation) (Lloyd et al. 1995) as influenced by soil water availability (available soil



moisture between 0-10 cm):  $\text{Log\_daily sapflux} = \text{log\_daytime potential evapotranspiration} + \text{log\_solar radiation} + \text{log\_}1/\text{max vapor pressure deficit} + \text{log\_max temperature} + \text{log\_max temperature}^2 + \text{log\_max temperature}^3 + \text{log\_cumulative volumetric soil water content at 0-10 cm}$ . This equation was fit for each tree separately to account for the day-to-day variation due to weather and soil moisture. Cumulative soil water content at 10 cm depth was chosen because it was best related to sap flux compared to other depths or combination of depths. In addition, a mixed model using all trees simultaneously was used with the random effects of tree, site, and day-of-year (DOY). A null model was conducted to determine variability in water use associated with random factors. A full model that included the functional equation was then conducted to determine how weather and water availability affect day-to-day variation of all trees combined.

## Results

### *Environmental conditions*

Compared with the 30 year normal annual rainfall of approximately 900 mm in north-central Oklahoma, 2011 was a dry year with a total rainfall of 677 mm at the study site. There were 81 days with precipitation with the most in any month occurring in May (14 events). Forty six events were smaller than the average 8.2 mm ( $\pm 1.3$  mm s.e.) and 22 events were larger than 10.0 mm with the largest event (52.6 mm) occurring in September (Figure 2). The 2011 summer (June-August) in Oklahoma was the hottest on record since 1954 and the third driest on record since 1936 (NOAA 2012). The soil volumetric water content (at 5, 20, 45, and 80 cm deep) for all sites reached a peak in

early February, decreased sharply in late February-March, increased again and was highly variable in May until it decreased again in the summer (Figure 2). The Hybrid site soil moisture followed the same pattern as the others, but with lower magnitude, especially at the 45 and 80 depths. Volumetric soil water was the most variable at 5 cm depth of all the sites. During 2011, the daily average temperature and average VPD were lowest in February and highest in August (Figure 3). The seasonal average solar radiation (Figure 4) and average daily potential evapotranspiration were: Winter, 11.7 MJ/m<sup>2</sup> and 2.1 mm; Spring, 20.5 MJ/m<sup>2</sup> and 5.1 mm; Summer, 23.7 MJ/m<sup>2</sup> and 6.9 mm; Fall, 12.3 MJ/m<sup>2</sup> and 2.7 mm.

#### *Tree water use*

Tree heights ranged from 3 to 14 m, DBH from 2 to 33 cm, sapwood areas from 10 to 370 cm<sup>2</sup>, and canopy area from 2 to 67 m<sup>2</sup> (Table 1). The open grown trees had an average of 138 kg ( $\pm 11$  kg s.e.) of dry foliage biomass, and the closed grown trees had an average of 35 kg ( $\pm 12$  kg s.e.) (Table 1). The larger canopy area trees used more water than smaller canopy area trees (Figure 5). When averaged across the year, daily average water use ranged from 2 liters for a 2 cm DBH open grown tree and a 5 cm DBH closed grown tree, to 80 liters for a 31 cm DBH open grown tree. Daily maximum water use (24 hour period) ranged from 4 liters (2 cm DBH open grown tree) to 152 liters (31 cm DBH open grown tree) (Table 2).

*Juniperus virginiana* water use fluctuated with seasonal and short-term weather patterns. For instance there were distinct patterns of water use that corresponded to air temperature, precipitation, and soil moisture (Figure 6). All trees transpired water year-

round, the lowest water use was in January when temperature and VPD were low and also in July during drought conditions (Figure 6). Water use decreased sharply in July, the month that was the hottest and driest compared to the others. The soil water moisture was also greatly reduced during this period, indicating a relationship between water use and soil water availability.

#### *Scaling tree water use to stands*

Average daily water use rates were well correlated to both DBH and canopy area (Figures 5). Based on DBH, open grown trees used greater amounts of water per unit of diameter than closed grown trees. There was no statistical difference in water use between trees with closed and open growth pattern when expressed on a canopy area basis.

The amount of water used on an annual basis can be estimated from the relationship between water use and canopy area (Figure 5). Based on our measurements, extrapolated to a hectare (10,000 m<sup>2</sup>) of continuous closed canopy, *J. virginiana* water use was 543 mm (5,425,800 liters/ha/year). Precipitation during 2011 at the research site was 677 mm (6,770,000 liters/ha). Therefore, with a completely closed canopy, a hectare of *J. virginiana* trees could use 80% of the incoming precipitation. Since about only 427 mm enters the soil after accounting for canopy interception of 37% (Caterina Chapter II), there is a deficit of 116 mm for 2011.

#### *Modeling J. virginiana water use*

For individual trees, the conceptual model explained an average of about 58% ( $\pm$  3) of daily sap flux variation. The coefficient of determination ranged from 0.32 to 0.75

(Table 3). For the model that included all trees, as well as DOY and site as random factors, sources of variation and equivalent variance component (significant at  $P \leq 0.05$ ) were site (0.03589,  $P = 0.19$ ), tree (0.02934,  $P = 0.003$ ), DOY (0.09053,  $P < 0.0001$ ), and residual (0.03878,  $P < 0.0001$ ). When the functional model that included weather variables was applied, sources of variation were site (0.03345,  $P = 0.19$ ), tree (0.02934,  $P = 0.003$ ), DOY (0.03101,  $P < 0.0001$ ), and residual (0.03894,  $P < 0.0001$ ). This represents a 66% decrease in variation due to DOY. The full model that predicts sap flux (with variables significant at  $P \leq 0.05$ ) was:

$$\log_{\text{Sap flux}} = -3.3954 + 0.2695 \log_{\text{ET}} + 0.09924 \log_{\text{ASOL}} + 0.2497 \log_{1/\text{MVPD}} + 0.04095 \log_{\text{T}_{\text{MAX}}} - 0.00009 \log_{\text{T}_{\text{MAX}}}^2 - 0.00001 \log_{\text{T}_{\text{MAX}}}^3 + 0.2316 \log_{\text{cVWC}_{-10}}$$

where, ET= daytime potential evapotranspiration; ASOL= daily solar radiation,  $1/\text{MVPD}$ = 1/maximum vapor pressure deficit,  $\text{T}_{\text{MAX}}$ = daily maximum temperature,  $\text{cVWC}_{-10}$ = volumetric soil water content between 0-10 cm depth.

## Discussion

Granier (1985) used the species *Pseudotsuga menziesii*, *Pinus nigra*, and *Quercus pedunculata* to generate the empirical equation to calculate sap flux. Even though some studies support the universal application of Granier's empirical equation (Braun and Schmid 1999, Loustau et al. 1996, Lu and Chacko 1998, McCulloh et al. 2007), others found that it varies with species (Bush et al. 2010, Lu et al. 2004, Steppe et al. 2010). Juniper trees are morphologically and physiologically different from most species on

which sapflow has been studied as they have narrow opening, thick walled and high strength tracheid cells (Willson et al. 2008). We developed our calibration based on the approach of Sun et al. (2012). Given the good fit of our equations, our calibration provides us confidence in our sap flux calculations for *J. virginiana*.

*Juniperus virginiana* trees used large quantities of water during periods of high atmospheric demand and favorable soil water content in 2011. Water used by *J. virginiana* was comparable with amounts used by species from the same genus. Both located in semiarid environments, a *J. occidentalis* tree of 44 cm basal diameter used a max of 132 liters/day (Eddleman and Miller 1991), and *J. ashei* trees with an average 23 m<sup>2</sup> ( $\pm 8.5$  m<sup>2</sup> s.e.) canopy area used between 20 and 125 liters/day (Owens 1996).

A functional relationship between foliage biomass, sapwood area, and transpiration should be expected. As such, larger trees conducted more water than smaller trees. When comparing growth type, open grown trees transpired larger volumes of water than closed grown trees of the same DBH. Trees growing in denser stands tend to grow slowly and may be older than open grown trees with the same diameter, which results in a higher percentage of heartwood (Lykins 1995). Also, open grown trees had more branches, larger canopies, and greater foliage weight than closed grown trees of the same DBH. There were no significant differences between growth types when expressing water use on a canopy area basis indicating that water use was directly correlated to canopy size regardless of growth type.

The differences of daily water use during late spring and during summer can be related to fluctuations in environmental factors. Transpiration increases on warm and sunny days in general (Jones 1998), but water uptake can be limited by low soil moisture

content under such climatic conditions (Oren and Pataki 2001). Water uptake by *J. virginiana* trees was substantially reduced but never ceased during the hot and dry summer of 2011 in Oklahoma, which is consistent with the report that *J. virginiana* is a drought tolerant species and is able to maintain physiological functions under low soil water potentials (Bahari et al. 1985, Eggemeyer et al. 2006) without incurring xylem cavitation (Willson and Jackson 2006). *Juniperus occidentalis* and *J. osteosperma* showed the same behavior during drought during which they had lower transpiration rates (Miller and Shultz 1987, West et al. 2008). Due to lower temperature and solar radiation, all trees used less water during winter compared to spring time. In central Missouri, *J. virginiana* sapling decreased stomata aperture due to low soil and air temperatures (Lassoie et al. 1983). *Juniperus virginiana* water conductance can be reduced by freezing temperatures especially if the freezing period occurs during a drought (Willson and Jackson 2006).

Water use was lower in January (beginning of the year) than December (end of year) even though temperatures were comparable probably because soil moisture was much lower in January than December. Low soil moisture in January was due to a prolonged drought during 2010 that continued into early 2011. Higher soil water content during December was due to increased precipitation inputs combined with lower evaporative demand from soil surface due to low temperatures (Schwinning and Sala 2004) as well as reduced solar radiation. Roots of *J. virginiana* can reach 7.5 m deep into the soil (Burns and Honkala 1990), and as with other juniper trees (Eddleman and Miller 1991, Eggemeyer et al. 2006, West et al. 2007), can access water from deep in the soil profile during conditions of low surface soil water and freezing temperatures.

Tree-to-tree and day of year influenced *J. virginiana* water uptake. Tree variation was due to differences related to size, canopy structure, leaf area, and other tree-specific factors. The majority of day of year variation could be explained by weather factors included in our functional relationship. The amount of variation due to weather explained for individual trees was similar to that from the model that included all trees. Our functional equation is biologically meaningful as compared to including all potential weather variables. Potential evapotranspiration and VPD drive the vapor diffusion from leaf to the atmosphere (Oren and Pataki 2001). Stomata primarily open during the day and their opening is generally proportional to radiation intensity (Kramer and Boyer 1995). Stomatal conductance responds positively to temperature until it reaches an optimum and begins to decrease (Lloyd et al. 1995). Soil moisture influences the response of stomatal conductance to the atmosphere demand (VPD), reducing transpiration when soil moisture is limiting (Oren and Pataki 2001).

Sap flow measurements from individual trees can be scaled to estimate stand water use using trees size measurements. Our results showed that tree canopy area and DBH are good predictors to scale tree water use. Tree DBH could be used to estimate water use from tree inventory data that typically includes DBH as a measurement of interest. When using DBH, however, it is necessary to know whether it is a low density stand with open grown trees, or a denser stand with closed grown trees. Canopy area did not need to be corrected to tree growth form and may offer an easy way to estimate water use based on aerial photographs.

Our estimate of water use of redcedar for a closed canopy was 542 mm. After accounting for interception (677 mm precipitation \* 63% net precipitation), only 427 mm

entered the soil during 2011. Therefore, 116 mm of precipitation is not accounted for. The surplus of water used was likely from depletion of stored soil water content. Trees can extend root beyond the canopy and this is important to maintain transpiration during dry periods (Scholes and Archer 1997). Also, trees may have used stored soil water. Even though there was little difference in volumetric soil water content in the upper meter between January and December, *J. virginiana* roots can reach up to 7.5 m deep into the soil (Burns and Honkala 1990). Another source of the difference is that encroached watersheds within the study area are not 100% closed canopy, which inflates the estimate of potential water use. More detailed measurements of canopy cover within stands are needed to increase the accuracy of this estimate. In addition, overestimates of daily sap flux or interception could have contributed to the 116 mm deficit. Regardless, annual *J. virginiana* water use can probably exceed precipitation in drier years.

Tallgrass species ( $C_4$  grasses) use water more efficiently than *J. virginiana* ( $C_3$  plants), but redcedar trees are more tolerant to drought and recover when soil moisture returns compared to grasses that senesce with water stress and are unable to recover (Eggemeyer et al. 2006). *Juniperus virginiana* can maintain stomatal conductance at low soil water potentials and demonstrate high water use efficiency (Eggemeyer et al. 2006, Willson and Jackson 2006). In addition, *J. virginiana* are evergreen with photosynthetically active leaves during all seasons, different from grasses that are dormant in winter time. Based on these factors and our measurements of *J. virginiana* water use that exceed annual precipitation during a dry year, *J. virginiana* can probably use more water than warm season grasses. Therefore, encroachment of *J. virginiana* into mesic grasslands will very likely to hasten depletion of soil water, especially during the



period of warm season grass senescence, creating conditions that limit saturation excess runoff production therefore decreasing streamflow. Better estimates of rainfall interception and grass water use are needed to make better a comparison of impact of *J. virginiana* on streamflow.

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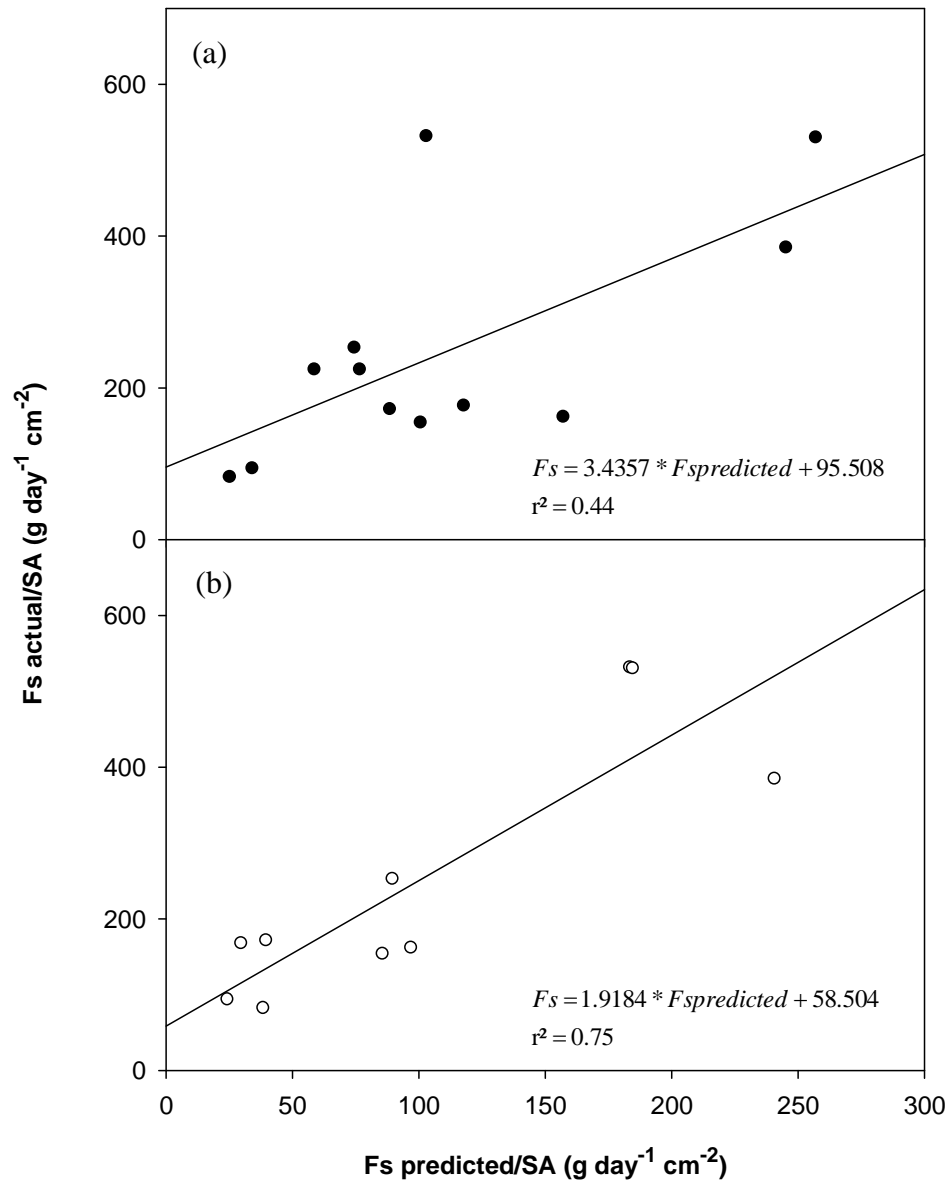
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**Table 1.** Characteristics from all *J. virginiana* trees used to investigate water use for 2011 with thermal dissipation probes in encroached mesic tallgrass prairie watersheds. DBH is the diameter at breast height (~1.37 m). Sapwood is the area of functional vascular tissue in a tree. Dry foliage weight was calculated from predictor equations described by Lykins (1995).

Tree ID	Growth type	DBH (cm)	Height (m)	Sapwood area (cm <sup>2</sup> )	Canopy area (m <sup>2</sup> )	Dry foliage biomass (Kg)
OG1	open	4	3	42	13	*
OG3	open	17	8	88	12	114
OG4	open	32	9	205	37	166
OG5	open	23	6	276	29	134
OG6	open	18	7	198	28	116
CG1	closed	20	12	157	14	18
CG2	closed	11	8	48	3	*
CG3	closed	7	5	16	1	*
CG4	closed	13	8	72	5	4
CG5	closed	27	14	231	28	33
CG6	closed	33	10	168	26	46
HO1	open	31	8	370	67	161
HO2	open	8	5	53	8	*
HO3	open	2	8	10	2	*
HO4	open	6	4	61	7	*
HC1	closed	5	6	10	2	*
HC2	closed	12	7	76	4	*
HC3	closed	21	9	125	3	74
HC4	closed	12	6	84	10	*

\*Tree DBH size did not fall into the range used by Lykins (1995) to predict dry foliage biomass.

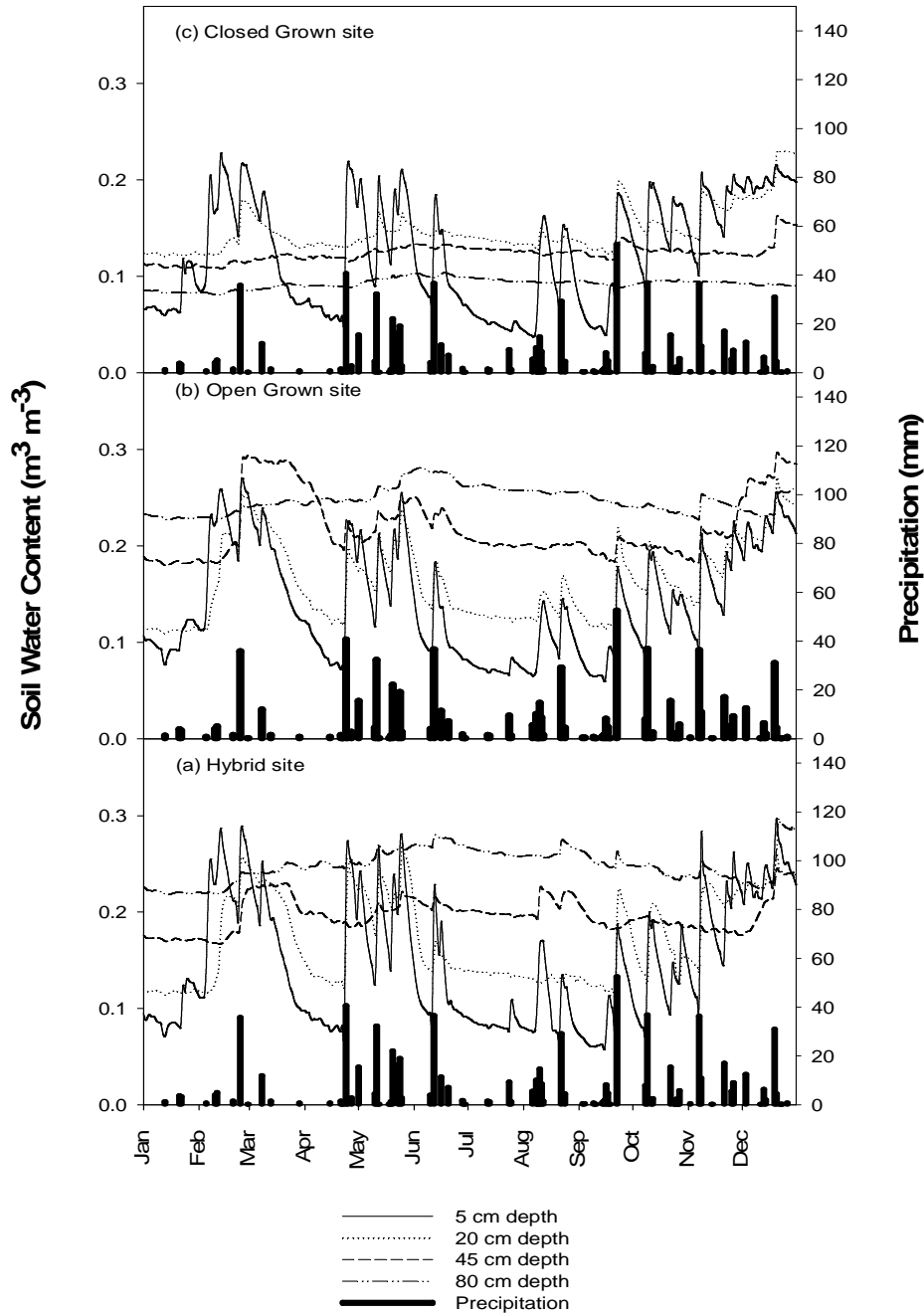


**Figure 1.** Relationship between actual water use (sapflux,  $F_s$ ) and the predicted water use for 10 mm probes (a), and for 30 mm probes (b). Actual water use was measured from a group of sample trees ( $n=12$  for (a) and  $n=10$  for (b)) during the calibration experiments. Predicted water use to each sample tree was calculated with the original estimated parameters from the equation described by Granier (1985).

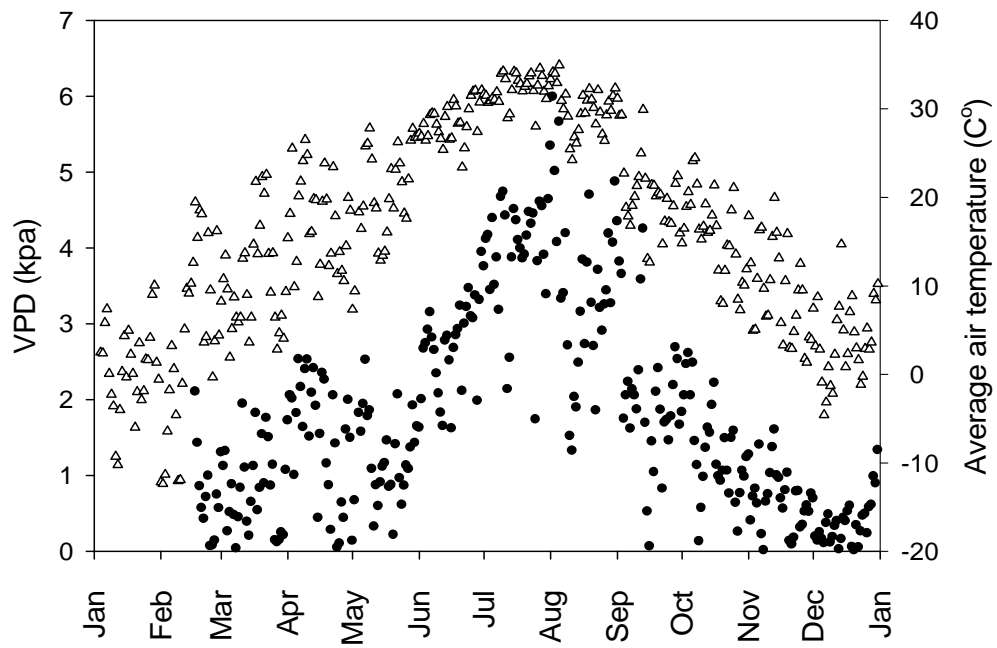


**Table 2.** Daily average, maximum and minimum water use for 2011 of all *J. virginiana* trees used to investigate water uptake in encroached mesic tallgrass prairie watersheds. Water uptake was measured using the thermal dissipation technique described by Granier (1985) on an hourly basis, and then was averaged to daily values.

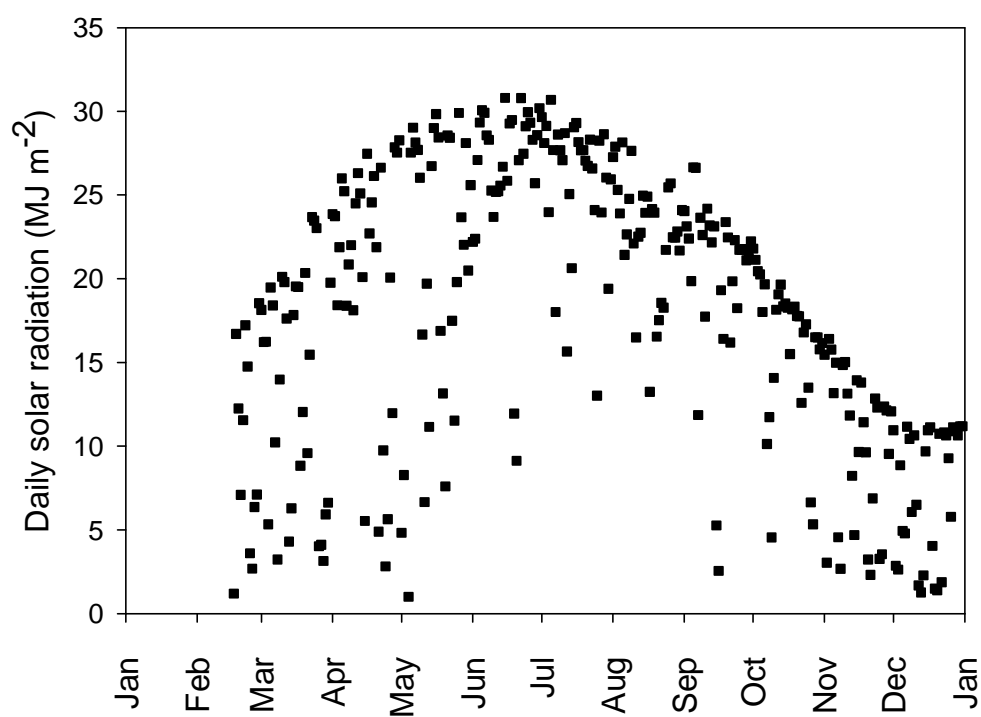
Tree ID	Average (liters day <sup>-1</sup> )	Maximum (liters day <sup>-1</sup> )	Minimum (liters day <sup>-1</sup> )
OG1	11	24	3
OG3	25	53	8
OG4	60	113	19
OG5	68	127	29
OG6	52	120	20
CG1	28	49	14
CG2	10	21	4
CG3	3	7	2
CG4	11	22	6
CG5	53	109	19
CG6	38	72	13
HO1	80	152	31
HO2	14	31	5
HO3	2	4	1
HO4	10	27	4
HC1	2	8	1
HC2	12	26	6
HC3	27	53	10
HC4	14	29	6
Overall average	27	55	11



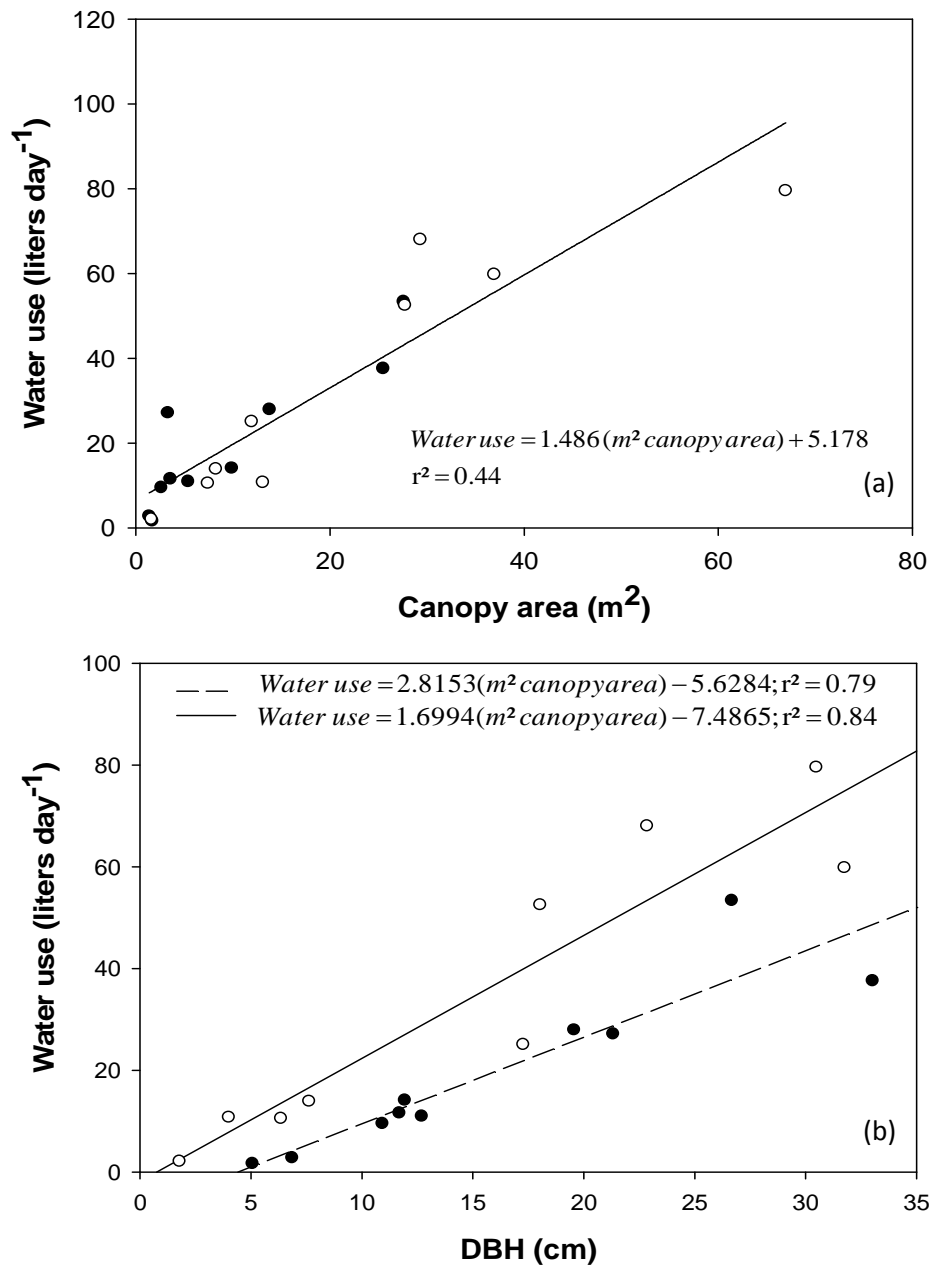
**Figure 2.** Daily precipitation and mean daily average of soil water content for all depths (5, 20, 45, 80 cm) for three sites: closed grown site (a), open grown site (b), and hybrid site (c). The soil water content for each depth was recorded every 15 minutes using ECH<sub>2</sub>O 5TE sensors and daily averages were calculated. Precipitation was recorded with automatic rain gauge located in an open area at the research site.



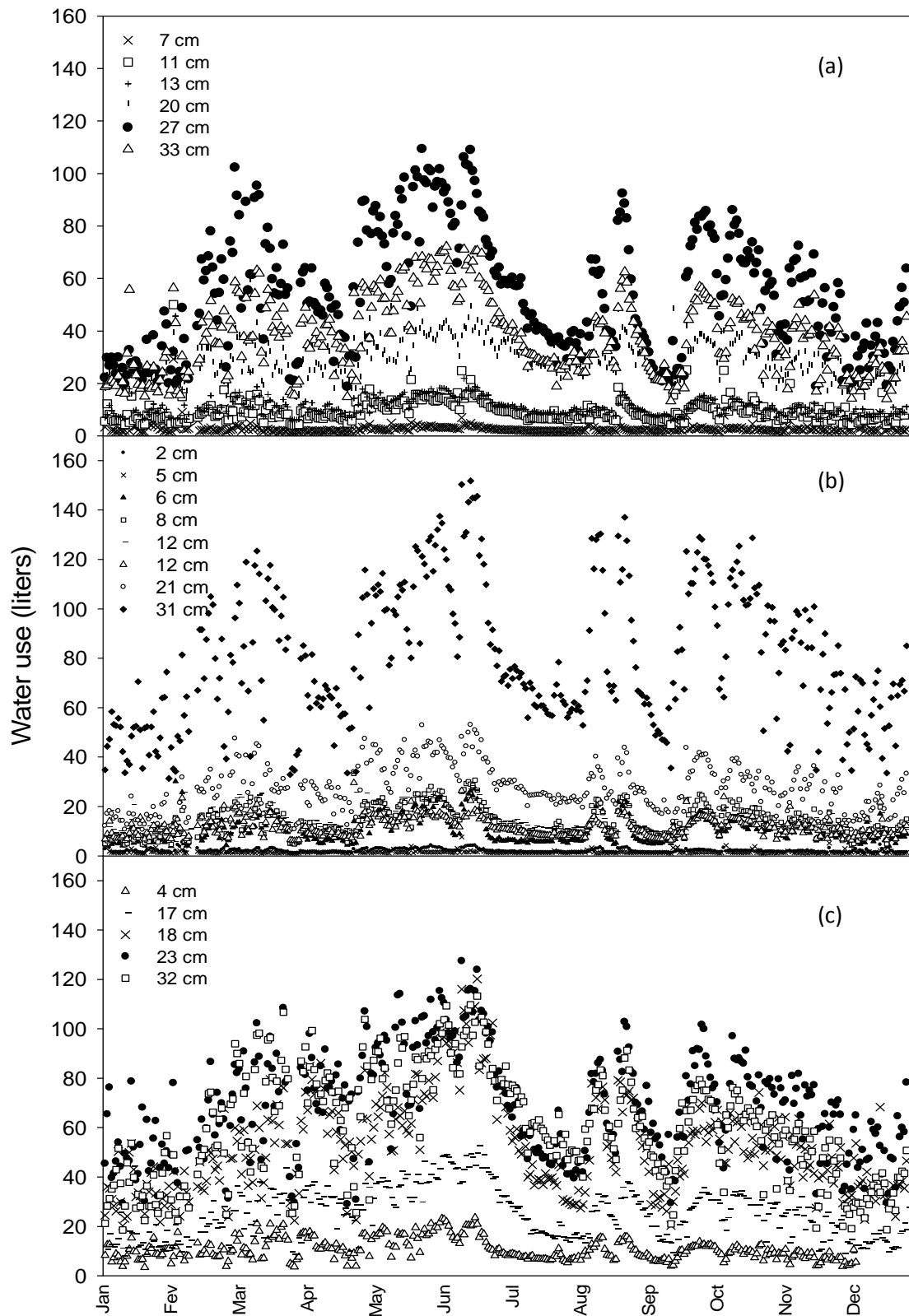
**Figure 3.** Max vapor pressure deficit (●) and daily average air temperature (Δ) patterns for 2011. Both variables were measured from a weather station located at the research site and the values correspond to daylight hours only.



**Figure 4.** Daily solar radiation for 2011, measured from a weather station located at the research site. The January and early February data are missing because the Pyranometer (Apogee SP-110, CS300) was installed at the site in February.



**Figure 5.** Relationship between 2011 average water use of each open grown (o), and closed (●) *J. virginiana* trees and (a) canopy area, and (b) DBH (diameter at breast height).



**Figure 6.** 2011 daily water use for *J. virginiana* trees with different DBH (diameter at breast height) from the (a) Closed grown, (b) Hybrid, and (c) Open grown sites.

**Table 3.** Individual *J. virginiana* tree water use (base-10 log) predictor models. Variables used were selected based on the underlying principle that transpiration rate is a function of atmospheric demand, stomatal conductance, soil water availability and the interaction of these three. The atmospheric demand was represented by daytime potential evapotranspiration (ET); stomatal conductance was represented by daily solar radiation (ASOL), and also by max vapor pressure deficit (1/MVPD), and a polynomial function of daily maximum temperature (TMAX \* TMAX<sup>2</sup> \* TMAX<sup>3</sup>); soil water availability was represented by volumetric soil water content between 0- 10 cm depth (cVWC-10).

Tree ID	Intercept	log_ET	log_ASOL	log_1/MVPD	log_TMAX	log_TMAX <sup>2</sup>	log_TMAX <sup>3</sup>	log_cVWC_10	r <sup>2</sup>
OG1	-3.66598	0.39519*	0.12668*	0.11955*	-0.00692	0.0018*	-0.00003778*	0.46964*	0.6165
OG3	-3.52639	0.55732*	0.01179	0.21589*	0.01448	0.00124*	-0.00003192*	0.44922*	0.7245
OG4	-3.75712	0.18465*	0.30215*	0.16209*	0.05393*	-0.00064222	-0.00000332	0.29811*	0.7564
OG5	-2.89476	0.45819*	0.05066	0.14179*	-0.004	0.00102*	-0.00002394*	0.31494*	0.6831
OG6	-2.69085	0.59077*	-0.08917	0.27573*	-0.03239*	0.0029*	-0.00004838*	0.33661*	0.5595
CG1	-3.83869	0.02247	0.20683*	0.22433*	0.06554*	-0.00125*	0.00001137	0.26706*	0.5432
CG2	-4.76512	0.13726	0.20709*	0.51451*	0.11446*	-0.00243*	0.00002328*	0.43028*	0.5818
CG3	-3.4835	0.16763	0.05635	0.37763*	0.03317*	-0.00012504	-5.97E-07	0.31887*	0.3627
CG4	-3.976	0.19792*	0.21045*	0.26202*	0.03405*	-0.00037498	9.13E-07	0.32766*	0.5737
CG5	-4.7697	0.31645*	0.213*	0.31243*	0.08781*	-0.00203*	0.00001708	0.57303*	0.6819
CG6	-3.9918	0.37732*	0.11802	0.22584*	0.05304*	-0.00106	0.00000653	0.46064*	0.6774
HO1	-3.58008	0.19433*	0.06808	-0.02453	0.0127	0.00088583	-0.00002468*	0.46606*	0.6765
HO2	-4.3318	0.31941*	0.04225	0.22716*	0.06157*	-0.00040074	-0.0000101	0.61366*	0.6274
HO3	-3.87619	0.2656*	0.02597	0.25802*	0.01929	0.0009801	-0.00002256*	0.50034*	0.5395
HO4	-4.73463	0.38599*	-0.05698	0.28779*	0.04468*	0.00088584	-0.00003093*	0.66423*	0.537
HC5	-3.22989	-0.06583	0.16288*	0.26027*	0.04123*	-0.00046524	0.00000278	0.13242*	0.1608
HC6	-4.40532	0.12165	0.11447*	0.2814*	0.05325*	-0.00007973	-0.00001084	0.45572*	0.5674
HC7	-4.14041	0.23254*	0.12744*	0.1256*	0.05296*	-0.00062444	-0.00000297	0.47999*	0.7406
HC8	-4.44828	0.15154	0.17388*	0.25058*	0.05085*	-0.00022216	-0.00000804	0.46463*	0.5882

\*Variables statistically significant to the model (P≤0.05)..

## CHAPTER IV

### GENERAL CONCLUSIONS

North-central Oklahoma has lost prairie species biodiversity, environmental services, and potential areas for grazing production due to *Juniperus virginiana* encroachment. This change of grassland to woodland probably increases evapotranspiration due to higher leaf area in trees compared to grasses. Oklahoma is currently in an extended drought period and any change on the water supply is a big concern. I conducted two experiments to measure the water intercepted by *J. virginiana* canopies and transpiration. My results can estimate evapotranspiration in *J. virginiana* and hereafter compare it with species from the tallgrass prairie to evaluate how *J. virginiana* encroachment affects the water budget.

*Juniperus virginiana* canopies intercepted an average of 37% of the rainfall during this study. However, this percent depended on the rainfall event magnitude and was lower during large events and much higher during small and low intense events. Stemflow represented 7 % of incoming precipitation. . Throughfall amount was not dependent on tree characteristics and it did not change due to differences in tree density. Rather, it depended on rainfall amount, intensity and duration. Stemflow was also not



dependent on site type and was dependent on rainfall amount and intensity, but also on tree size. Stemflow per canopy area decreased as tree DBH (diameter at breast height) size increased, mainly when considering trees of open grown pattern. Larger *J. virginiana* trees have thicker bark and higher absorption capacity.

*Juniperus virginiana* trees in this study used an average of 27 liters per day in 2011. However, this value was much higher depending on for large trees and during times of high atmospheric demand and ample soil moisture. On a warm and sunny day with plenty soil water available, a tree of 67 m<sup>2</sup> of canopy area used 152 liters of water. Water use by *J. virginiana* trees was dependent on potential evapotranspiration, solar radiation, vapor pressure deficit, temperature, and soil water content between 0-10 cm depth. *Juniperus virginiana* water use can be scaled based on tree canopy area, or DBH, and was found to probably exceed 2011 annual precipitation after subtracting canopy interception.

*Juniperus virginiana* stands decrease soil water input in north-central Oklahoma tallgrass prairies by decreasing the water reaching the soil surface. In addition, stands potentially use more water than infiltrates the soil during dry years. When compared to grasses species, *J. virginiana* has higher leaf area and aboveground biomass, factors that relate to higher rainfall interception. *Juniperus virginiana* uses water during all seasons, different from grasses that are dormant in winter time. In addition, *J. virginiana* are more tolerant to drought compared to grasses that senesce with water stress and are unable to recover. However, water use of grass species still needs to be measured from the grass

watersheds within this study area before any conclusion about the difference between *J. virginiana* and grasses evapotranspiration amount can be made.

## VITA

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